Performance Monitoring of Liners: Parameter Identification

CRC-P: Smart Linings for Pipe and Infrastructure
Sub-project 3: Smart Sensing and Application

October 2018

Associate Professor Sarath Kodagoda
Dr. Karthick Thiyagarajan
Centre for Autonomous Systems
Faculty of Engineering and Information Technology
University of Technology Sydney, NSW 2007
Australia

Contents

1. Background

A large proportion of water and wastewater infrastructure pipelines are nearing the end of their remaining useful service life. Replacement of failing pipes can cost millions of dollars to the water utilities and invoke major disruptions to the public and nearby surroundings. Liners/coatings are used in water and wastewater pipelines to minimize the effects of pipe degradation and to strengthen the integrity of the pipes. Exploiting liner/coating technologies for fit for purpose applications is a potential avenue for extending the service life of water and wastewater pipe infrastructure whilst saving capital and operational expenditure. However, liners/coatings have limited industry standards, specifications and tools to confirm their post-installation and long-term performance.

The Government of the Commonwealth of Australia had funded a Cooperative Research Centres Project (CRC-P) on 'Smart Linings for Pipe and Infrastructure'. This project focuses on establishing standards and specifications, and fit for purpose liners/coatings with smart sensing/robotic capabilities to enhance the utilization of the linings in collaboration with Water Services Association of Australia (WSAA), liner/coating manufacturers, liner/coating applicators, water utilities and researchers.

With the motive of the CRC-P, a team from the University of Technology Sydney (UTS) is developing smart sensing and robotic systems for post application quality assurance (PAQA) and long-term performance monitoring (LTPM) of liners/coatings under the sub-project 3. The first Milestone of the project is to identify the best parameters for monitoring to establish PAQA and LTPM. In achieving Milestone 1, a literature review, a survey and expert interviews were conducted to identify the most crucial liner/coating parameters in order to develop sensing technologies. This report presents discussions about liner types, literature review, survey outcomes and finally, the list of finalized parameters.

2. Liner/Coating Types and Products

Within the scope of the CRC-P, the sub-project 3 focuses on developing sensing technologies for performance monitoring of four different types of liners/coatings namely,

i. **Calcium Aluminate Cement (CAC) Coating** – In general, this is a hydraulic binder mainly made up of mono-calcium aluminate ($CaO.Al_2O_3$) and contains small grains of calcium aluminate clinker.

ii. **Geo-polymer Coating** – In general, this is a cement mortar based on fumed silica, blast furnace slag and fly ash for resisting acid attacks in wastewater pipelines.

iii. **Cured-in-place-pipe (CIPP) Liner** – In general, this is a flexible tube made out of felt, fiberglass or combination saturated with a 'hardenable' resin system.

iv. **Spray Liner** – In general, this is a resin based epoxy formulation that mainly consists of polyurethane and polyurea and sprayed onto a surface to harden faster.

The scope of the CAC and Geo-polymer coatings are limited to wastewater pipes while the CIPP and Spray liners are limited to water pipes. The WSAA led project steering group chose the specific liner/coating products, which are to be used for the development of the sensing systems in the sub-project 3. Table 1 lists the chosen liner/coating products.

Table 1: Chosen liner/coating products for sub-project 3.

Type	Liner Product	Manufacturer	Pipe Type
CAC	Extrema-Dur S1	Bisley	Wastewater Pipe
Geo-polymer	Renderoc G	Parchem	Wastewater Pipe
CIPP	Aqua Pipe	Sanexen	Water Pipe
Spray	Subcote^{TM} FLP	Radius Subterra	Water Pipe

3. Literature Review: Liner/Coating Defects

In this section, the literature review of liner/coating defects is presented for different types of wastewater and water pipe liners and coatings. The literature review focuses on reviewing the potential defects that can be developed just after the curing process of the liners (short-term) and in the long-term period. The defects are reported to be formed by substandard materials, inadequate surface preparation, poor workmanship or inadequate curing of the applied liners.

3.1 CAC Coating Defects

This section presents the types of CAC coating defects based on the reported literature [1, 2, 3, 4, 5] and based on discussions with the researchers. The defects include the following (they are not arranged in a particular order):

- Inadequate compressive and bond strength
- Cracks, pinholes
- Leakage through the coating
- Uneven surface, poor joints and coating terminations, poor general finish
- Inadequate cover to reinforcement
- Excessive mortar loss during application
- Surface bulges
- Delamination
- Excessive distortion, surface roughness

- Inadequate coating thickness (finished thickness < 90% of nominal coating thickness)
- Excessive variations in thickness
- Surface softening
- Crazing (A network of fine random cracks on the surface of coating)
- Shrinkage
- Poor curing
- pH reduction

3.2 Geo-polymer Coating Defects

This section presents the types of Geo-polymer coating defects reported in literature [6, 7] and based on the suggestions of industry experts/researchers (they are not arranged in a particular order):

- Lining thickness
- Improper adherence
- Voids
- De-bonding
- Bubbles
- Inadequate curing
- Cracking and crazing
- Delamination

3.3 CIPP Liner Defects

This section presents the types of CIPP liner defects reported in the literature [6, 7, 8, 9, 10] and based on the suggestions of industry experts/researchers. The defects include the following (they are not arranged in a particular order):

- Collapsed pipe sections
- Uneven thickness (includes areas of uneven stretching)
- Improper/uneven curing
- Variations in host pipe diameter
- De-bonding/ Liner peeling
- Wrinkles
- Voids
- Excessive longitudinal fold after liner installation and other folds
- Cracks
- Bulges
- Dimples
- Pin holes

- Tearing/liner damage
- Long-term strength loss
- Shrinkage

3.4 Spray Liner Defects

This section presents the types of spray liner defects reported in the literature [6, 7, 8] and based on the suggestions of industry experts/researchers. The defects include the following (they are not arranged in a particular order):

- Liner thickness variations
- Degree of adhesion to the host pipe (Improper adhesion)
- Liner disbondment (Improper bonding)
- Liner collapse
- Bubbles (observed 1-3 inches in diameter)
- Folds
- Material slipping down the pipe wall due to gravity
- Improper curing
- Liner slump
- Ringed lining (variable thickness)
- Shadow effects
- Blisters/blowholes (voids/bulges)
- Sagging
- Debonding / peeling of liners
- Tearing or liner damages
- Liner strength reduction
- Shrinkage

4. Survey

This section presents the survey outcomes highlighting the most important defect parameters related to wastewater and water pipe liner/coating types.

4.1 Overview

The smart sensing and application survey questionnaire (see the Appendix 1) was sent out by WSAA to the project partners and experts. Twenty one members took part in the survey, which includes 11 utilities, 5 applicators, 1 manufacturer, 2 researchers and 2 in the "others" category, which are The Water Research Foundation (WRF) and WSAA. The survey consisted of four types of liner/coating categories: CAC, Geo-polymer, CIPP and Spray liners. The scope of the CAC and Geo-polymer applications were limited to wastewater pipes while the scope of CIPP and Spray liner applications were limited to

water pipes. Further, the survey broadly categorizes the defects into short-term (immediately after the recommended curing period) and long-term defect types.

4.2 Survey Outcomes for Coating Defects: Wastewater Pipes

- **Defects - Short-term Monitoring**: Delamination resulted as the most important defect for CAC and Geo-polymer coatings for short-term monitoring.

- **Defects - Long-term Monitoring**: Cracking and crazing was the most favoured defect for CAC whereas de-bonding was chosen by the majority as the most important long-term defect for Geo-polymer coatings.

Table 2 presents the important defects for CAC and Geo-polymer coating types in the short-term and long-term period from the survey results.

Table 2: Important coating defects for wastewater pipes based on the survey.

Coating Type	Defects: Short-term monitoring	Defects: Long-term monitoring
CAC	*Delamination	Cracking & Crazing
Geo-polymer	*Delamination	**De-bonding

* Delamination – detachment of material from the coating or host pipe excluding the bonding interface.
** De-bonding – detachment of coating material from the host pipe at the bonding interface.

4.3 Survey Outcomes for Liner Defects: Water Pipes

- **Defects - Short-term Monitoring**: For the CIPP liners, improper curing was chosen by a slight majority as the most significant defect type for short-term monitoring whereas de-bonding was chosen for the Spray lining for the same category.

- **Defects - Long-term Monitoring**: In the case of CIPP liner pipes, liner damages were chosen by the majority as a significant defect type for long-term monitoring. Similar to the Geo-polymer, de-bonding defect was chosen as the most significant defect for long-term monitoring of Spray liners.

Table 3 presents the important liner defects for CIPP and Spray liner types in the short-term and long-term performance monitoring based on the survey results.

Table 3: Important liner defects for water pipes based on the survey

Liner Type	Defects: Short-term Monitoring	Defects: Long-term Monitoring
CIPP	Improper Curing	Liner Damages
Spray	De-bonding	De-bonding

5. Proposed Liner/Coating Defects: Based on the Survey, Literature and Expert's Feedback

This section presents the proposed liner/coating defects to be considered for the wastewater and water pipe infrastructure performance evaluation in the short-term and long-term periods based on the survey, literature and expert's feedback.

5.1 Coating Defects: Wastewater Pipe Coatings

According to the survey, delamination resulted as the most important defect to be monitored for the CAC and Geo-polymer coating products in the short-term period. However, reference [1] downplays the pre-mature failure of CAC caused by delamination. Further discussions with the researchers point to uneven thickness of the coatings as a more crucial parameter for evaluating the CAC and Geo-polymer coatings in the short-term period.

Further, from the survey, 'cracking & crazing' and 'de-bonding' have resulted as the most significant long-term defects for CAC and Geo-polymer coatings respectively. However, expert practitioners and researchers feedback suggested that thickness loss over time is relatively more significant than other defects for both CAC and Geo-polymer coatings. Table 4 tabulates the proposed crucial defects for CAC and Geo-polymer type wastewater pipe coatings. Acid permeation is also proposed as a crucial parameter to measure and hence further discussions are carried out for fine tuning the parameter list.

Table 4: Proposed defects for short-term and long-term monitoring: wastewater pipe coatings.

Coating Type	Defects: Short-term Monitoring	Defects: Long-term Monitoring
CAC	Uneven Thickness	Thickness Loss
Geo-polymer	Uneven Thickness	Thickness Loss

5.2 Liner Defects: Water Pipe Liners

According to the survey, 'improper curing' and 'liner damages' have resulted as the most significant short-term and long-term defects for CIPP liner type. However, discussions with the experts from water utilities and researchers revealed that liner imperfections such as folds, wrinkles, dimples and bulges are thought to be more common defects than improper curing. Interestingly, from the survey outcomes, liner imperfections resulted as the second most important defect, slightly less than the first (improper curing). Therefore, liner imperfections are considered as a potential monitoring parameter for CIPP liners for both short-term and long-term monitoring.

According to the survey, 'de-bonding' was chosen as the most significant short-term and long-term defect for Spray liners. The experts have a different opinion on the adhesion or de-bonding. Ideally, the liners need to be properly bonded to the pipes for structural support as well as to not allow water to pass between the liner and host pipe (this will allow leakage if the host pipe failed). In case of a host pipe failure, it is desirable to de-bond so that the liner still can perform. Therefore, the de-bonding was not considered as the top priority and hence, liner imperfections are agreed as a possible short-term and long-term liner defect. These liner imperfections include sagging, folds, liner peeling (de-bonding), tears, damages and blisters [2]. In addition, experts have also suggested liner thickness measurement is important for spray liners. Table 5 tabulates the proposed crucial defects for CIPP and Spray type water pipe liners.

Table 5: Proposed defects for short-term and long-term monitoring for water pipe liners.

Liner Type	Defects: Short-term Monitoring	Defects: Long-term Monitoring
CIPP	Liner Imperfections	Liner Imperfections
Spray	Liner Imperfections & Uneven Thickness	Liner Imperfections & Uneven Thickness

6. Finalized Liner/Coating Defects

This section presents the finalized liner/coating defects for the wastewater and water pipes based on extensive discussions with researchers, sub-project 3 steering group, Project Steering Group (PSG) and the Committee of Management (CoM) team of the CRC-P project. Table 5 and Table 6 presents the list of finalized defect parameters to be considered for the coatings/liners in the Sub-Project 3 scope of work.

6.1 Finalized Defects: Wastewater Pipe Coatings

For the short-term performance evaluation of CAC and Geo-polymer coatings, 'uneven thickness' was decided as a crucial defect parameter after consultations with the researchers, experts, industry practitioners, project steering group and committee of management of the CRC-P.

Although 'thickness loss' was proposed earlier for performance evaluation of CAC and Geo-polymer coatings in the long-term period, some researchers and water utilities preferred and supported the 'acid permeation'. The rationale being, the coatings are used to prevent or delay the acid attacks on sewer walls and hence acid permeation is a direct measure of how the coatings are performing. Further, it was argued that the thickness loss may not be a good parameter as the material itself may expand during the process of corrosion. After many discussions, the Committee of Management has agreed to research on measuring the acid permeation of the applied CAC and Geo-polymer coatings as the long-term performance monitoring parameter through non-destructive techniques (NDT). It was agreed that the sensor development for acid permeation is blue-sky with associated high risk of not having industry ready outcomes during the CRC-P period. Table 6 presents the finalized defect parameters to be monitored for the performance evaluation of CAC and Geo-polymer coatings in the short-term and long-term period.

Table 6: Finalized defects for short-term and long-term monitoring: wastewater pipe coatings.

Coating Type	Defects: Short-term Monitoring	Defects: Long-term Monitoring
CAC	Uneven Thickness	Acid Permeation
Geo-polymer	Uneven Thickness	Acid Permeation

6.2 Finalized Defects: Water Pipe Liners

For the short-term and long-term performance evaluation of the CIPP type liners, 'liner imperfections' was proposed as a crucial defect parameter. The proposed defect parameter was discussed in the Project Steering Group (PSG) meeting and the Committee of Management (CoM) has agreed to finalize the proposed 'liner imperfection' defect for performance monitoring of CIPP liners in the short-term and long-term period.

For the Spray liners, 'liner imperfections' and 'uneven thickness' were proposed as the significant defect parameters for performance evaluation in the short-term and long-term period. During the PSG meeting, the CoM decided to finalize the proposed 'liner imperfections' and 'uneven thickness' defect parameters for performance monitoring of Spray liners in the short-term and long-term period. Table 7 presents the finalized defect parameters to be measured for the performance evaluation of CIPP and Spray liners in the short-term and long-term period.

Table 7: Finalized defects for short-term and long-term monitoring for water pipe liners.

Liner Type	Defects: Short-term Monitoring	Defects: Long-term Monitoring
CIPP	Liner Imperfections	Liner Imperfections
Spray	Liner Imperfections & Uneven Thickness	Liner Imperfections & Uneven Thickness

7. Concluding Remarks

In the CRC-P project, Milestone-1 of the sub-project 3 aims to identify the parameters of interest for short-term (post application quality assurance) and long-term performance monitoring of wastewater and water pipe liners/coatings. In this context, the following presents the concluding remarks based on the literature, survey and expert's opinion:

- For the short-term performance monitoring (post application quality assurance) of CAC and Geo-polymer coated wastewater pipes, uneven thickness of the applied coating was finalized to be the most important defect parameter.

- For the long-term performance monitoring of CAC and Geo-polymer coated wastewater pipes, the CoM/PSG has decided to proceed with monitoring acid permeation. Measuring acid permeation non-destructively is challenging and it will require significant innovation. This introduces a risk that delivering an industry ready technology may be infeasible during the CRC-P timeline.

- For the CIPP type liners applied to the water pipes, liner imperfections were identified and finalized as the crucial defects to be monitored in both short-term and long-term periods.

- For the Spray lined water pipes, liner imperfections and uneven thickness of the applied linings were finalized as the most significant defects that need to be monitored in the short-term and long-term period.

Bibliography

[1] Sydney Water, "SS 210 Corrosion Protection and Rehabilitation of Maintenance Holes," Sydney Water.

[2] M. Valix, “Survey and Review of Current Rehabilitation and Coating Technologies for Many Entry Sewer Pipes and Manholes with Protective Coatings - SP2 Report,” Sydney, 2011.

[3] M. Valix, “Service Life Model for Calcium Aluminate Cement Based on Field Test Results - SP2 Report”.

[4] M. Valix, “Conversion and Its Effect on CAC Corrosion - Based on Accelerated Corrosion Tests”.

[5] F. Saucier and S. Lamberet, “Calcium Aluminate Concrete for Sewers: Going from Qualitative to Quantitative Evidence of Performance,” in *Concrete in Aggressive Aqueous Environment, Performance, Testing and Modeling*, Toulouse, France, 2009.

[6] J. Matthews, A. Selvakumar, S. Vaidya and W. Condit, “Large-Diameter Sewer Rehabilitation Using a Spray-Applied Fiber-Reinforced Geopolymer Mortar,” *Practice Periodical on Structural Design and Construction,* vol. 20, no. 4, 2015.

[7] J. Matthews, W. Condit, S. Vaidya, R. Stowe and A. Selvakumar, “Performance Evaluation of an Innovative Fiber Reinforced Geopolymer Spray-Applied Mortar for Large Diameter Wastewater Main Rehabilitation in Houston, TX,” U.S Environmental Protection Agency, 2014.

[8] E. Kampbell , D. Downey, W. Condit and A. Selvakumar, “Quality Assurance and Quality Control Practices for Rehabilitation of Sewer and Water Mains,” U.S. Environmental Protection Agency, 2011.

[9] S. Das, *Evaluation of Cured-in-Place Pipe Lining Installations,* Canada: Thesis - University of Alberta , 2016.

[10] J. Matthews, W. Condit, . R. Wensink, G. Lewis and A. Selvakumar, “Performance Evaluation of Innovative Water Main Rehabilitation Cured-in-Place Pipe Lining Product in Cleveland, Ohio,” U.S. Environmental Protection Agency, 2012.

[11] D. Vasilikis and S. A. Karamanos, “Mechanical behavior and wrinkling of lined pipes,” *International Journal of Solids and Structures,* vol. 49, no. 23-24, pp. 3432-3446, 2012.

[12] A. M. Riahi, *Short-Term and Long-Term Mechanical Properties of CIPP Liners,* Waterloo: Thesis - University of Waterloo, 2015.

[13] O. Awe, *Testing of Innovative Pipe Renewal Liners for Renovation of Potable Water Distribution Pipelines,* Waterloo: Thesis - University of Waterloo, 2014.

[14] “POLYMERIC-BASED STRUCTURAL REHABILITATION OF WATER MAINS CASE STUDY,” Peterborough Utilities Commission , 2013.

[15] J. Matthews, W. Condit, R. Wensink, G. Lewis , R. Sterling and A. Selvakumar, “Performance Evaluation of Innovative Water Main Rehabilitation Spray-on Lining

Product in Somerville, NJ. U.S.," United States Environmental Protection Agency (EPA), Washington, 2012.

Appendix

Survey result analysis graphs presenting the distribution of the first choice among the number of respondents for monitoring the short-term and long-term defects of each category. X-axis indicates the potential liner/coating defects and Y-axis corresponds to the number of respondents saying the defect as the first choice.

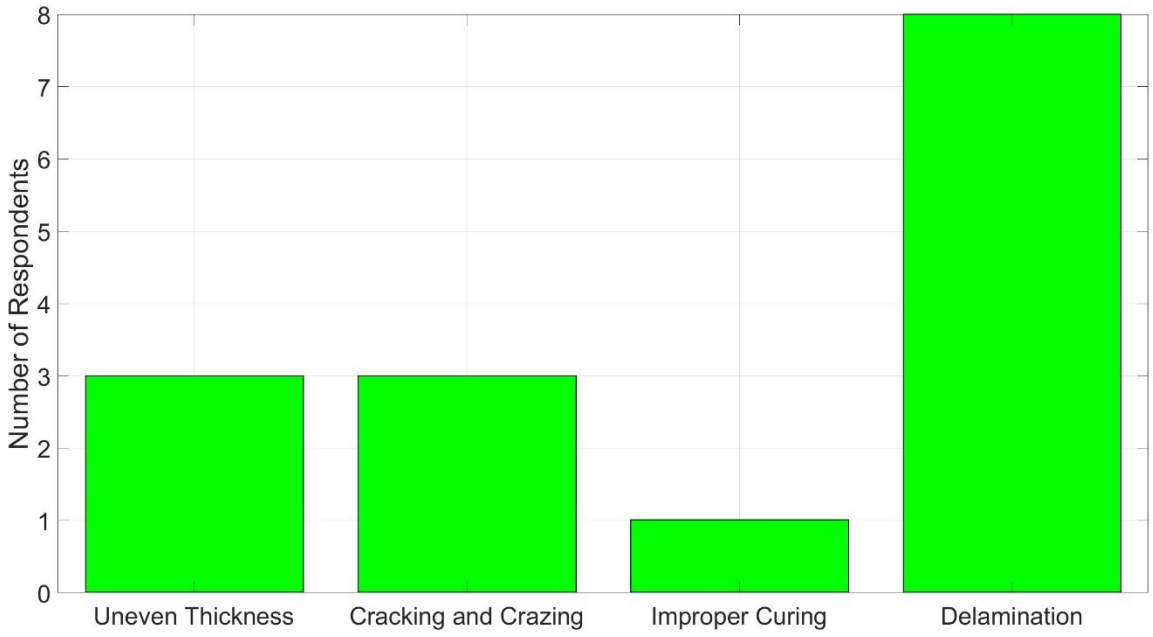

Figure 1: Short-term defects of CAC coating.

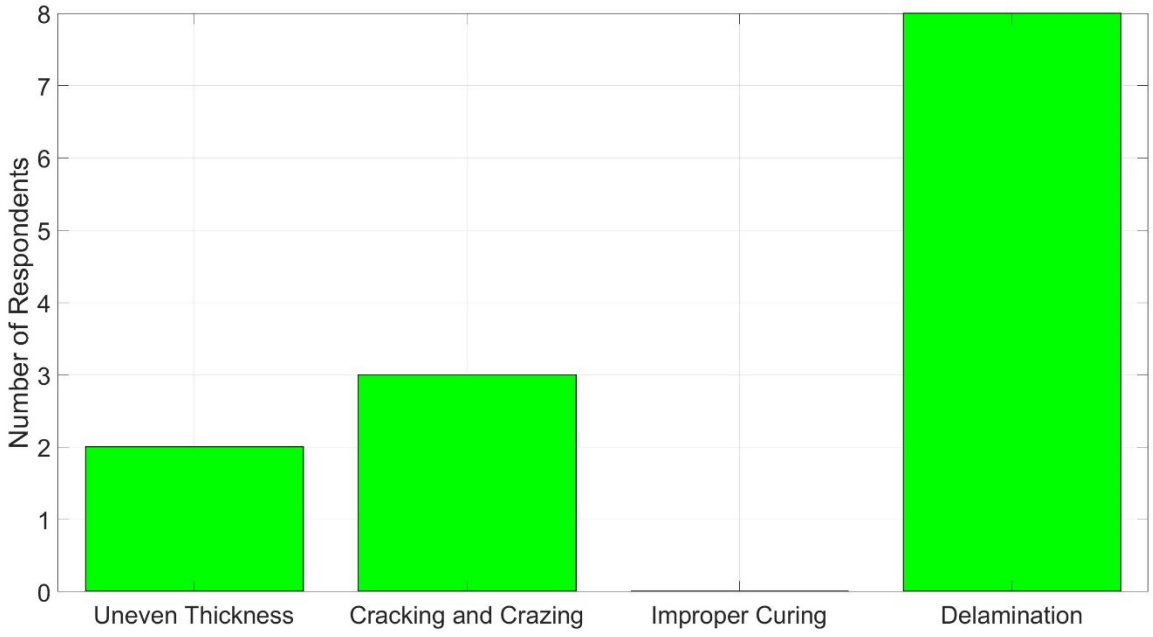

Figure 2: Short-term defects of Geo-polymer coating.

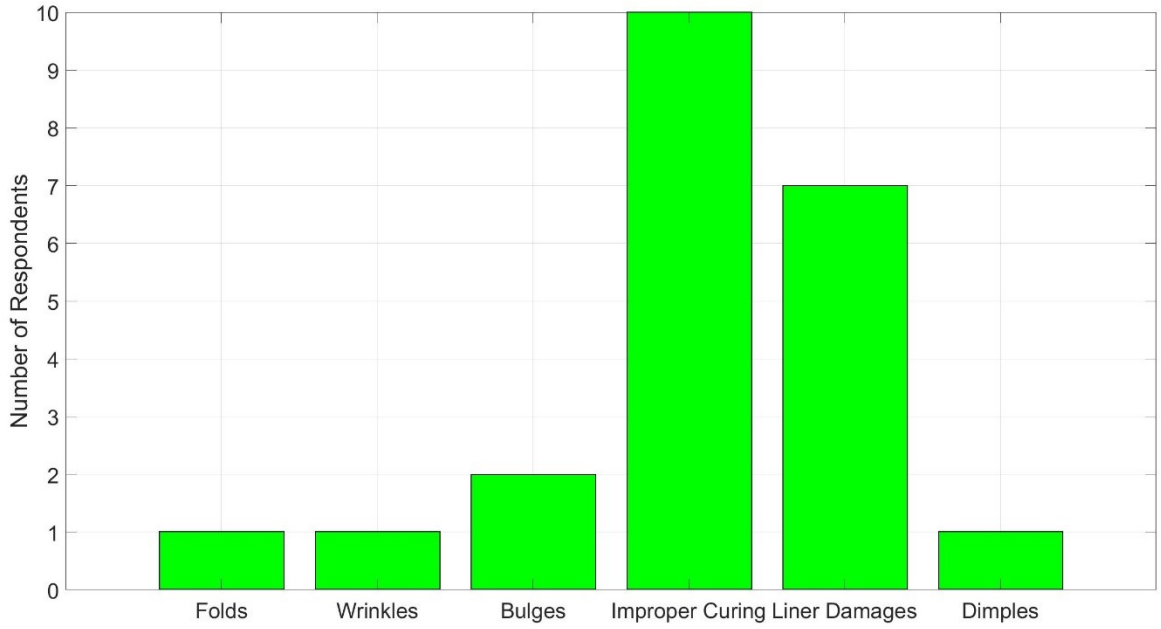

Figure 3: Short-term defects of CIPP liner.

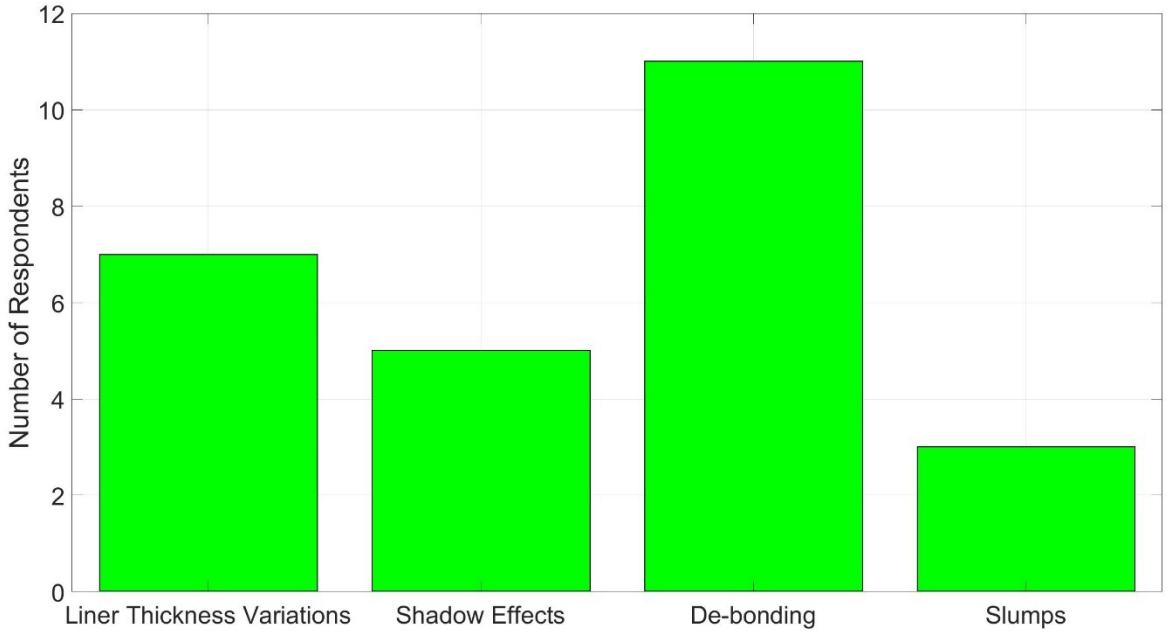

Figure 4: Short-term defects of Spray liner.

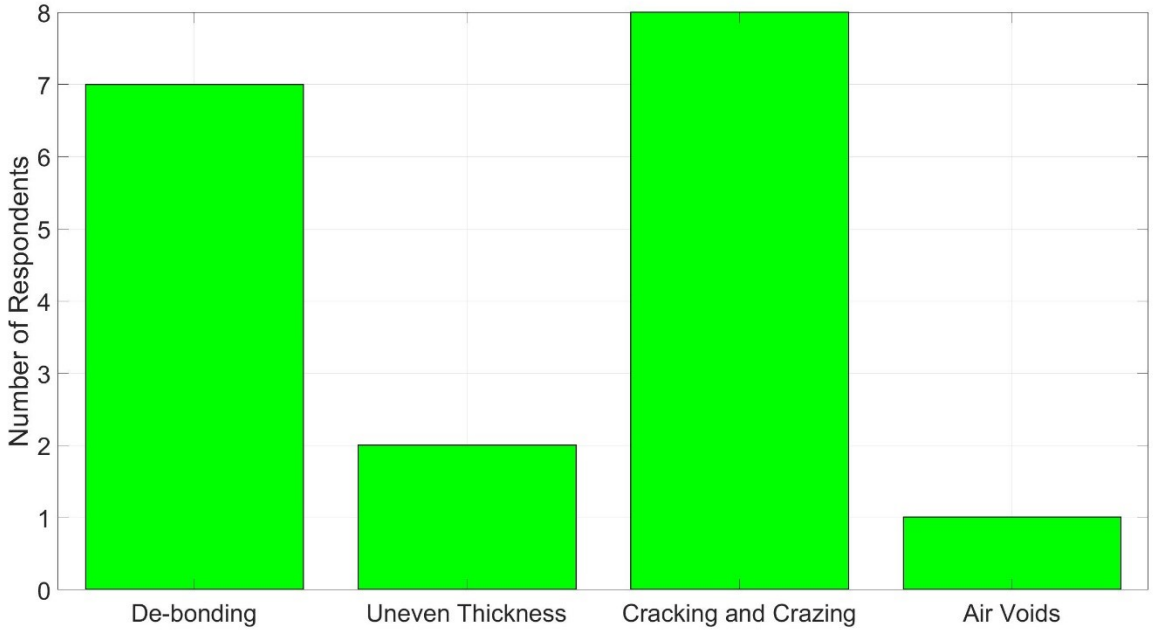

Figure 5: Long-term defects of CAC coating.

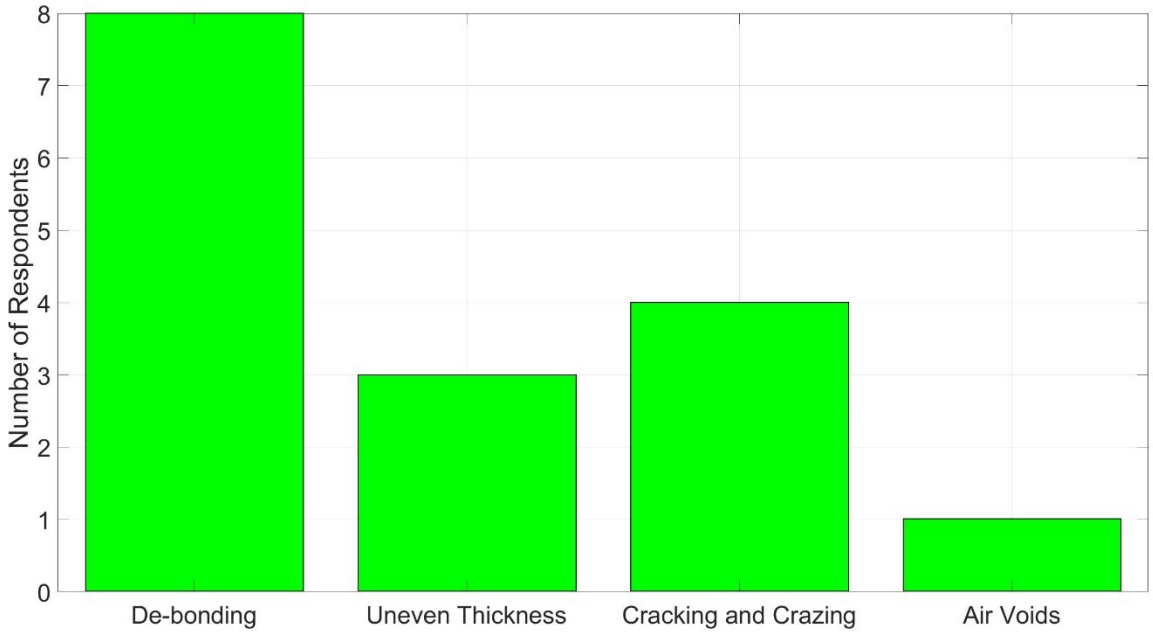

Figure 6: Long-term defects of Geo-polymer coating.

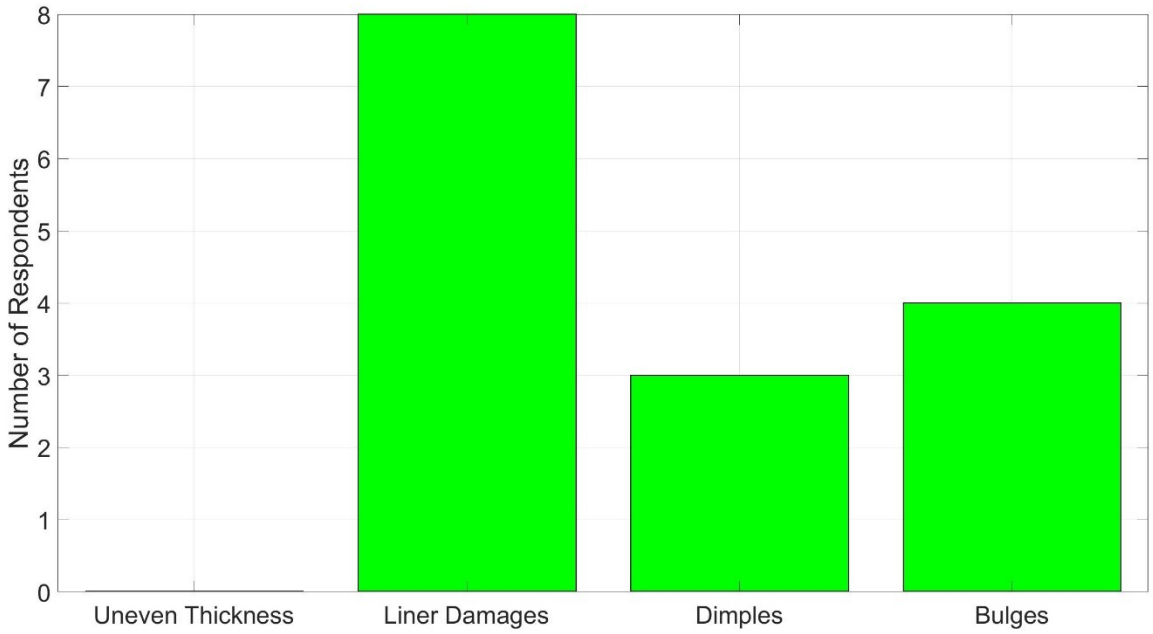

Figure 7: Long-term defects of CIPP liner.

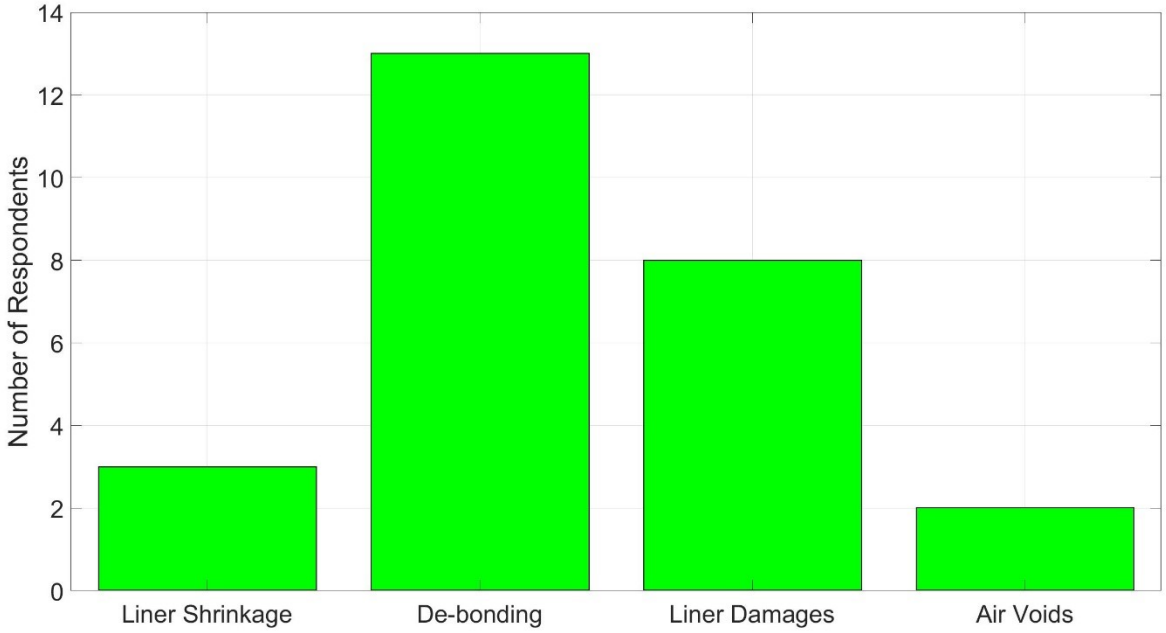

Figure 8: Long-term defects of Spray liner.

Survey Questionnaire

Responses cannot be edited

CRC-P: Smart Sensing & Application Survey Questionnaire

This CRC-P project on Smart Linings for Pipe and Infrastructure is a collaboration between WSAA, manufacturers, applicators, utilities, and researchers.

This questionnaire is aimed to gain insights into defects to evaluate the quality of applied Calcium Aluminate Cement (CAC) liners, Geo-polymer liners, Cured-In-Place-Pipe (CIPP) liners and Spray liners.

This survey has 5 sections and it will only take 10-15 minutes of your time. Your participation is very valuable and we appreciate you taking time to complete it. Your name and email will only be used to follow up with you if needed.

Name

Organisation

Email

Choose the potential liner defects that can occur immediately after the recommended curing period.

Select the top 3 in order: 1 for most important and IR for Irrelevant defect type for this particular liner type

1. CAC

	1	2	3	IR
Uneven Thickness	○	○	○	○
Cracking and Crazing	○	○	○	○
Improper Curing	○	○	○	○
Delamination	○	○	○	○

Any other?

2. Geo-polymer

	1	2	3	IR
Uneven Thickness	○	○	○	○
Cracking and Crazing	○	○	○	○
Improper Curing	○	○	○	○
Delamination	○	○	○	○

Any other?

3. CIPP

	1	2	3	IR
Folds	○	○	○	○
Wrinkles	○	○	○	○
Bulges	○	○	○	○
Improper Curing	○	○	○	○
Liner Damages	○	○	○	○
Dimples	○	○	○	○

Any other?

4. Spray

	1	2	3	IR
Liner Thickness Variations	○	○	○	○
Shadow Effects	○	○	○	○
Improper Bonding	○	○	○	○
Slumps	○	○	○	○

Any other?

Choose the potential liner defects developed over long-time period.

Select the top 3 in order: 1 for most important and IR for Irrelevant defect type for this particular liner type

5. CAC

	1	2	3	IR
Debonding	○	○	○	○
Uneven Thickness	○	○	○	○
Cracking and Crazing	○	○	○	○
Air Voids	○	○	○	○

Any other?

6. Geo-polymer

	1	2	3	IR
Debonding	○	○	○	○
Uneven Thickness	○	○	○	○
Cracking and Crazing	○	○	○	○
Air Voids	○	○	○	○

Any other?

7. CIPP

	1	2	3	IR
Uneven Thickness	○	○	○	○
Liner Damages	○	○	○	○
Dimples	○	○	○	○
Bulges	○	○	○	○

Any other?

8. Spray

	1	2	3	IR
Liner Shrinkage	○	○	○	○
Debonding	○	○	○	○
Liner Damages	○	○	○	○
Air Voids	○	○	○	○

Any other?

Current Technologies in Practice

9. Write down any current technologies that are used to identify potential liner defects (short-term or long-term. Example: CCTV Inspection)

Thanks for taking part in this survey

Please leave any other comments/suggestions below.