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Abstract: Despite the significant investments made in the use of cured-in-place pipe (CIPP) rehabilitation technologies, quality assurance (QA) and quality control (QC) practices can vary widely among municipalities, and CIPP liner evaluations are mostly restricted to periodic CCTV inspections. The information in this paper is derived from a multi-year project funded by the U.S. Environmental Protection Agency (US EPA). The study included a first of its kind retrospective evaluation of retrieved CIPP liners that were in service between 5 and 34 years at 18 different locations. This paper focuses on an assessment of the types of testing that were used during a pilot study to perform the CIPP retrospective evaluation. After performing the suite of tests, both visual inspection and flexural testing were found to be the key QA/QC assessment techniques. However, liners’ specific gravity was also found as a useful QA/QC tool and pursuing several other possibilities for non-destructive or minimally-invasive testing for measuring in situ physical properties of liners appeared feasible.

Subjects: Tunnelling & Underground Engineering; Waste & Recycling; Water Engineering; Life-Long Design

Keywords: life-cycle performance; rehabilitation; Wastewater; CIPP; testing; QA/QC

ABOUT THE AUTHORS
S. Alam has been affiliated with the Trenchless Technology Center, Louisiana Tech University since 2007. He has interest in innovative technology, methods, and material development for infrastructure rehabilitation and management. Some of his works include deteriorated concrete pipe simulation, pipe material-soil friction coefficients evaluation, CIPP resin and liner performance, infrastructure retrospective assessment.

The team for this project was made up of experts in trenchless technology, material science, innovative quality control testing, and cured-in-place pipe (CIPP). This program was funded by the U.S. EPA over the course of more than five years and included several municipalities as project partners from across the North America. The research reported by the team in this paper focuses on the retrospective evaluation of trenchless materials, which was one of the major needs identified by the stakeholders at an industry expert workshop hosted by the EPA in New Jersey in 2006.

PUBLIC INTEREST STATEMENT
Sewer pipelines around the world are in dire need of repair. Traditional excavation and replacement approaches of buried pipe repair due to the additional socio-economic costs are typically much more expensive than the non-disruptive methods known as trenchless a technology that has such costs at their minimal. The most common trenchless technology repair method is called cured-in-place pipe (CIPP), which has been used for more than 45 years. Despite this wide usage there is no standard approach available in the public domain for tracking the performance of CIPP and other trenchless repair materials. This paper focuses on an assessment of the various types of testing that were developed based on a pilot study and used as part of the CIPP retrospective evaluation project. Many techniques were evaluated and visual inspection and certain destructive tests were found to be the most appropriate assessment techniques.
1. Introduction

Limited information on the in situ performance of rehabilitation methods used for prolonging the service life is widely available to the municipalities. Nevertheless, when the time comes the municipalities have to decide on deploying one of such trenchless technology repair techniques. With some CIPP liners having been in service for over 30 years in North America, municipalities are expressing a strong interest in the collection of data regarding the condition and life-cycle performance of these CIPP liners to validate assumptions made regarding the anticipated design life, which was originally established based on accelerated testing. The outcome of such an evaluation will support the decision-making and cost/benefit evaluations, as well as provide shared experiences among municipalities in a systematic and transferable manner. This paper report results from a comprehensive series of material performance evaluation tests performed on a CIPP liner specimens exhumed after been in service for 5 to 30 plus years, thus representing one of the early CIPP installations in North America. In addition to visual inspection, annular gap, and in situ ovality measurement, samples were prepared for measuring specific gravity, bending, tensile, thickness, hardness, and porosity properties of the material. Results were compared with design values available during the time of installation and with controlled specimens prepared in the lab. Similar retrospective studies of CIPP have been attempted by Alzraiee, Bakry, and Zayed (2013), Lystbaek (2007), Macey and Zurek (2012), Macey, Zurek, Clinch, Delaurier, and Sorokowski (2013) and Shelton (2012). The study is important for the city decision makers and engineers as the outcome provided insight into different evaluation procedures, degradation mechanisms and deterioration rates of in situ, in-service CIPP liners and therefore establishes justification for this work.

2. Current practice

A study conducted by Kampbell et al. (EPA, 2011) showed substantial number of CIPPs deployed for sewer rehabilitation had matured to their design age as per the outdated ASTM standards for CIPP. Therefore, recommendations on addressing CIPP QA/QC are now often directed by owner or project engineer. However, introduction of newer technologies (e.g. pressurized steam and UV curing), often challenge their acquaintance in some QA/QC cases. This is especially true for UV cured systems as glass composites having their dominant strength in the circumferential direction requires field samples must be tested using curved beams. However, the ASTM standards (e.g. D2990, D5813, F1216, F1743, and F2019) cover no scope for testing curved beam samples like ISO 11296-4 does. D2990 and D5813 focus on long term service performance evaluation of CIPP, based on 10,000-h strain and chemical resistance tests on coupon samples while installation methods are described in F1216, F1743, and F2019. D5813 addresses load case classification as well as required resin grade of CIPP, but was not written for CIPPs subjected to internal pressure condition. F1216 describes installation using inversion process, while F1743 and F2019 provide guidance for pulled-in-place installation. In addition to the installation methodology, F2019 also focuses on using entire glass fiber tube. Currently the ASTM subcommittee is updating the F2019 to include testing of curved beam samples; but upgrading of F1216 and F1743 is yet to be started.

In addition to the ASTM standards outlined above, additional QA/QC procedures are sometimes recommended by technology vendors where submittal documents include details on the material pre-qualification testing. The thermosetting resin impregnated felt systems in CIPP are hardened by activating heat or UV light initiator with heat produced using hot water or steam, and UV light. Thus, the key control points of a CIPP installation include proper saturation and finished thickness of felt, proper catalyzation, appropriate curing and cooling of resin. In some countries, such as Germany, CIPP products are tested more often (IKT, 2011) to a suite of standard tests (IKT, 2015).

3. Visual inspection

Visual inspection of CIPP using close-circuit television (CCTV) cameras mounted on a robot is an important QA/QC measure. Although defect coding procedures in pipes are well established in the US (e.g. NASSCO PACP, 2015), the recommended post-installation CCTV inspection practices have recently been addressed. Likewise, periodic inspection practices are not well defined in terms of the type of equipment, operating parameters during inspection, frequency, etc. Therefore, the protocols
used on this study for visual inspection were performed on a case by case basis and often found varying.

The retrieved 18 samples were found in good shape with little evidence of deterioration. In all the locations, CCTV inspection showed openings for lateral connections are likely to cause damage and potential to reduce the design life of installed liner. Visual CCTV checks are repeatable as long as the pipe remains accessible (e.g. not collapsed). However, consistency of evaluations can be an issue without operator care and standard assessment protocols.

4. Flexural strength and modulus

Short term flexural (ASTM D790) properties indicate structural integrity and stiffness of the liner and its stability when subjected to long-term buckling. Flexure properties are key design parameters (Araujo, Sabeshan, & Yao, 2010) with specified minimum values per ASTM F1216, F1743, and F2019.

In this study, the flexural modulus (Table 1) ranged from 206,805 psi (1,426 MPa) to 477,609 psi (3,293 MPa) with an average and standard deviation of 317,503 psi (2,189 MPa) and 70,171 psi (483 MPa), respectively. The flexural strength ranged from 4,469 psi (30.8 MPa) to 8,592 psi (59 MPa) with an average and standard deviation of 6,594 psi (45 MPa) and 1,066 psi (7 MPa), respectively for the same sites. The percent standard deviation for flexural modulus was higher (22.1%) in

| Sample retrieve location | Sample ID in database | Age (years) | Average values |
|--------------------------|-----------------------|-------------|----------------|
|                          |                       |             | Flexure – D790, psi (MPa) |
|                          |                       |             | Strength | Modulus |
| Columbus 36 in. (900 mm) | COL-36-1989           | 21          | 6,039 (42) | 206,805 (1,426) |
| Columbus 8 in. (200 mm) | COL-8-2005            | Crown       | 7,199 (50) | 366,563 (2,527) |
|                          |                       | SL          | 6,422 (44) | 328,118 (2,262) |
|                          |                       | Invert      | 5,627 (39) | 343,470 (2,368) |
| Denver 8 in. (200 mm)   | DEN-8-1984            | Crown       | 6,454 (45) | 329,768 (2,274) |
|                          |                       | SL          | 6,712 (46) | 340,044 (2,345) |
|                          |                       | Invert      | 7,103 (49) | 336,209 (2,318) |
| Denver 48 in. (1200 mm) Downstream | DEN-48-1987-DS | 23          | 7,031 (48) | 302,960 (2,089) |
| Denver 48 in. (1200 mm) Upstream | DEN-48-1987-US | 23          | 5,575 (38) | 223,165 (1,539) |
| Edmonton 10 in. (250 mm) | EDM-10-1994           | 19          | 6,135 (42) | 331,333 (2,285) |
| Edmonton 8 in. (200 mm) | EDM-8-1994            | 19          | 6,816 (47) | 364,788 (2,515) |
| Houston 21 in. (525 mm) | HOU-21-1996           | 17          | 6,893 (48) | 337,638 (2,328) |
| Houston 18 in. (450 mm) | HOU-18-1996           | 17          | 7,204 (50) | 338,565 (2,334) |
| Indianapolis 42 in. (1050 mm) | IND-42-1986         | 25          | 4,712 (32) | 237,264 (1,636) |
| Nashville Dunston 8 in. (200 mm) | NASH-8-1994         | 19          | 6,833 (47) | 301,724 (2,080) |
| Nashville Wyomig 8 in. (200 mm) | NASH-8-2004         | 9           | 5,497 (38) | 282,460 (1,948) |
| NYC 15 in. (375 mm)     | NYC-15-1989           | 23          | 7,978 (55) | 477,609 (3,293) |
| NYC 12 in. (300 mm)     | NYC-12-1988           | 24          | 7,200 (50) | 285,177 (1,966) |
| Northbrook 12 in. (300 mm) | NB-12-1979           | 34          | 7,761 (54) | 322,360 (2,223) |
| Winnipeg Richard 30 in. (750 mm) | WIN-30-1978        | 34          | 8,592 (59) | 452,136 (3,117) |
| Winnipeg Kingsway 18 in. (450 mm) | WIN-18-1978        | 34          | 6,779 (47) | 323,930 (2,233) |
| Winnipeg Mission 30 in. (750 mm) | WIN-30-1984        | 28          | 4,469 (31) | 245,753 (1,694) |
| Average                 |                       |             | 6,594 (45) | 317,503 (2,189) |
| Standard deviation      |                       |             | 1,066 (7)  | 70,171 (684) |
| Percent standard deviation |                       |             | 16.2       | 22.1 |

*Samples received at TTC was not large enough to test for this parameter but test data for the liners was received from City of Winnipeg. See also the data from Macey et al. (2013).

Shaded boxes indicate data that do not meet the current minimum ASTM requirement.
comparison to flexural strength (16.2%). Four of the 18 samples tested, the flexural modulus were below the F1216 requirement of 250,000 psi (1,724 MPa) and one of them also did not meet the flexure strength requirement. It was noted regarding WIN-30-1984, which did not meet the ASTM requirement, that the “low flexural strength value was associated with a liner with visible installation related issues” although its service was meeting requirements. Therefore, it is difficult to determine the deterioration stage by the liner flexure properties that had existed since installation.

ASTM D790 is easily repeatable, but the sample preparation and testing procedure for QA/QC purposes during installation can lead to significant variations (Araujo & Yao, 2014) between the tests values and those that would be properly representative of the installed liner.

5. Tensile strength and modulus

Tensile properties (strength and modulus) obtained in D638 has no direct association to the design of CIPP liners installation standards (F1216, F1743, and F2019) and are only needed for pressurized pipelines. Therefore, the tensile testing was included in the EPA retrospective study to provide

| Sample ID in database | Age (yrs) | Average values | Tensile – D638, psi (MPa) |  |
|-----------------------|-----------|----------------|--------------------------|---|
|                       |           | Strength       | Modulus                  |   |
| COL-36-1989           | 21        | 2,958 (20)     | 315,259 (2,174)          |   |
| COL-8-2005            | 5         | 4,020 (28)     | 404,641 (2,790)          |   |
|                       | Crown     | 3,696 (25)     | 338,849 (2,336)          |   |
|                       | SL        | 3,882 (27)     | 344,275 (2,374)          |   |
|                       | Invert    |                |                          |   |
| DEN-8-1984            | 25        | 3,047 (21)     | 411,789 (2,839)          |   |
|                       | Crown     | 2,990 (21)     | 401,069 (2,765)          |   |
|                       | SL        | 3,051 (21)     | 422,006 (2,910)          |   |
|                       | Invert    |                |                          |   |
| DEN-48-1987-DS        | 23        | 2,995 (21)     | 382,420 (2,637)          |   |
| DEN-48-1987-US        | 23        | 3,208 (22)     | 426,787 (2,943)          |   |
| EDM-10-1994           | 19        | 3,241 (22)     | 436,710 (3,011)          |   |
| EDM-8-1994            | 19        | 3,653 (25)     | 510,132 (3,517)          |   |
| HOU-21-1996           | 17        | 3,409 (24)     | 465,322 (3,208)          |   |
| HOU-18-1996           | 17        | 3,252 (22)     | 450,985 (3,110)          |   |
| IND-42-1986           | 25        | 2,718 (19)     | 351,294 (2,422)          |   |
| NASH-8-1994           | 19        | 3,436 (24)     | 375,807 (2,591)          |   |
| NASH-8-2004           | 9         | 2,672 (18)     | 400,926 (2,764)          |   |
| NYC-15-1989           | 23        | 3,729 (26)     | 554,101 (3,821)          |   |
| NYC-12-1988           | 24        | 3,275 (23)     | 324,406 (2,237)          |   |
| NB-12-1979            | 34        | 4,402 (30)     | 433,541 (2,989)          |   |
| WIN-30-1978           | 34        | 4                  | 433,541 (2,989)          |   |
| WIN-18-1978           | 34        | 4                  | 433,541 (2,989)          |   |
| WIN-30-1984           | 28        | 4                  | 433,541 (2,989)          |   |
|                       | Average   | 3,323 (23)     | 413,460 (2,851)          |   |
| Average               |           | 455 (3)         | 65,961 (455)             |   |
| Percent standard deviation |      | 13.7           | 16.0                     |   |

*Samples received at TTC not large enough to test for this parameter.*
additional measures of the structural capabilities of the retrieved CIPP liner samples. Mean tensile modulus and standard deviation were 413,460 psi (2851 MPa) and 65,961 psi (455 MPa), respectively and mean tensile strength and standard deviations were 3,323 psi (23 MPa) and 455 psi (3.1 MPa) (see Table 2). Similar to the flexural results, the percent standard deviation was less for the strength properties (13.7%) than for the modulus properties (16.0%).

Alike the D790, the D638 is also easily repeatable subjected to sample preparation and testing procedure. However, the principal issue involved in the D638 testing is gripping the test specimens. Poor gripping can induce premature tensile failure or slippage at the grips and use of pneumatic grips was found producing better results.

6. Thickness

Thickness of a liner in conjunction with flexural properties is ASTM F1216 requirements for resistance to external buckling (Harada, Doherty, Leffler, McClanahan, & Osborn, 2011) and therefore, a critical design parameter for estimation of the service life.

In this study thickness measurements were carried out (Table 3) in numerous locations at the field and lab using caliper, ruler, or ultrasonic device based on whether the liner was retrieved within the host pipe or a sample was cut from within a person-entry pipe. Thicknesses on three liners were found to be 20–30% lower than the specified thickness while two liners had thicknesses more than specified (i.e. 110 and 112% of required value).

| Sample ID in database | Age (yrs) | Average values | Specific gravity | Ovality |
|-----------------------|-----------|----------------|-----------------|---------|
|                        |           | Shore D hardness | Thickness       |         |         |
|                        |           | Inner Outer % Change | Design thickness Measured thickness % Change |         |         |
| COL-36–1989            | 21        | 64.8 78.6 17.5 | 15.0 11.9 −20.7 | 1.17    | NA      |
| COL-8–2005             | 5         | 62.7 81.4 23.0 | 6.0 5.7 −4.8    | 1.11    | 5.07%   |
| DEN-8–1984             | 25        | 58.9 77.0 23.5 | 6.0 5.9 −1.7    | 1.16    | 7.4%    |
| DEN-48–1987-DS         | 23        | 65.2 78.9 17.4 | 18.0 12.5 −30.6 | 1.07    | NA      |
| DEN-48–1987-US         | 23        | 46.6 62.7 25.7 | 13.5 14.2 5.2   | 1.08    | NA      |
| EDM-10–1994            | 19        | 68.6 78.1 12.2 | 5.0 4.7 −6.0    | 1.25    | 2.7–3.3%|
| EDM-8–1994             | 19        | 68.2 79.2 13.9 | N/A 4.8 N/A     | 1.25    | 4.5–5.75%|
| HOU-21–1996            | 17        | 61.2 61.3 0.1 | N/A 10.7 N/A    | 1.17    | 1.4%    |
| HOU-18–1996            | 17        | 65.4 75.7 13.6 | N/A 11.0 N/A    | 1.18    | 1.7%    |
| IND-42–1986            | 25        | 57.0 65.7 13.3 | N/A 22.2 N/A    | 1.08    | NA      |
| NASH-8–1994            | 19        | 65.2 72.2 9.7  | N/A 5.6 N/A     | 1.14    | 3.7%    |
| NASH-8–2004            | 9         | 64.6 67.4 4.1  | N/A 7.1 N/A     | 1.21    | 3.6%    |
| NYC-15–1989            | 23        | 73.3 72.1 −1.7 | N/A 7.3 N/A     | 1.31    | NA      |
| NYC-12–1988            | 24        | 57.7 58.7 1.7  | N/A 7.1 N/A     | 1.15    | NA      |
| NB-12–1979             | 34        | 65.6 76.0 13.7 | 6.0 4.7 −21.7   | 1.19    | 0.33–0.38%|
| WIN-30–1978            | 34        | 57.4 65.8 12.8 | 6.0 6.6 10.0    | 1.21    | NA      |
| WIN-18–1978            | 34        | 54.1 60.9 11.2 | 6.0 6.7 11.6    | 1.14    | NA      |
| WIN-30–1984            | 28        | 57.3 64.9 11.8 | N/A 22.8 N/A    | 1.07    | NA      |
| Average                |           | 61.88 70.92 12.41 | 9.52 −6.50 | 1.16    |         |
| Standard deviation     |           | 6.26 7.48 7.71 | −5.55 14.89 0.07 |         |         |
| Percent standard deviation |    | 10.1 10.5 − | − 58.3 − | 5.7    | |
The applicability of this test for monitoring deterioration of an aged liner depends on the obtained cleaned hard surface that produces representative results. In the case of a softer surface caliper readings may lead to inconsistent results and significantly depends on the tester’s experience. The ultrasonic thickness measurement equipment for CIPP liners provided inconclusive results on the collected samples and therefore further detailed evaluation is recommended for smart deployment of ultrasonic thickness measurement equipment for CIPP QC at this time.

7. Annular gap
Annular gap measurements provide information about potential shrinkage or displacement of the liner and the size of the annular gap impacts buckling resistance due to external hydrostatic pressure. Liners with little or no annular gap are capable of resisting higher external pressures and therefore, enforcement of required internal pressures and proper cool-down requirements are essential.

Field measurements of the annular gap between the host pipe and liner were taken on both sides of retrieved samples using feeler gauge at the crown, spring line, haunch, invert, and in between at 45°. A set of sample readings are shown in Figure 1. In this study, the annular gaps ranged between less than 0.005 inches (0.13 mm) to a maximum of localized 0.421 inches (10.7 mm) for the oldest liner in the study (installed in 1979). Measurement of the annular gap requires invasive cutting of the liner or cutting out a composite sample of the host-pipe and liner and therefore is not easily repeatable.

8. Ovality
Ovality shows liner’s distorted shape in comparison to circular cross-sections and is an important assessment factor for liner’s resistance to buckling under external pressure. Equation X1.1 in F1216 has an ovality reduction factor for determination of the allowable external hydrostatic pressure; which, in turn, is also used in equations X1.2 and X1.3. The maximum measured ovality (see Table 3) was 7.4% for an individual reading within one sample, but the cross-section profile for this sample exhibited local irregularities that were interpreted as conforming to the inner surface of the host pipe.

A profile plotter was used to accurately map the shape of the interior surface of the liner. The system features a linear variable displacement transducer (LVDT) connected perpendicularly to the axis of the shaft of a motor-gear system capable of moving forward or backward while spins at the center and guides the LVDT to rotate around the liner’s inner circumference. An encoder provides position information regarding the location around the pipe. Keeping the shaft right on the center is
a big challenge involved in this method. For small diameter liners a computer software image-analysis-based technique was tested. Here, traced actual liner’s shape on a paper was converted to a DXF file format using computer software and compared to a circle drawn based on already known inner diameter of the host pipe. This method was found convenient, but requires cutting of a liner sample at each section.

Combination of both methods may be applied for development of an in situ non-intrusive technique, however, further study is required. Moreover, laser-based techniques capable of identifying the inner radii of liner can also be used for tracking any distortion or change in ovality over time and may be an indication to a shorter design life.

9. Specific gravity and porosity
Specific gravity and porosity of liner specimen can provide useful information on constituent components and associated quality. Specific gravity of all 18 samples was determined per ASTM D792 and with typical proportions of resin and felt and no filler materials, the theoretical limits of specific gravities for CIPP range from 1.075 (10% porous) to 1.191 (0% porous). Presence of Talc as a filler material changes the range between 1.224 (10% porous) and 1.360 (0% porous) with an assumption of felt occupying 14% of the final volume with the remaining volume taken by resin and filler. The average specific gravity for the 18 liners was found between 1.07 and 1.25.

The specific gravity of a liner suggests a potential correlation with liner mechanical properties and structural parameters (Figure 2) and is an indicator of the quality of the liner. However, determining
accurate and repeatable values for the specific gravity of CIPP samples obtained from different locations of the same sample still presents challenges in the QA/QC programs.

Porosity on the samples was measured using a Mercury Intrusion Porosimeter (MIP) with an intention of finding correlation between deterioration and porosity plus specific gravity. However, tests produced unrealistically high specific gravities as the MIP intrude mercury under high pressure and result into squeezing of the CIPP material comparatively softer with concrete specimen and therefore, is not a good QC approach.

10. Surface hardness

Surface hardness was measured at beginning, following the ASTM D2240 (Shore D Durometer) and D2583 (Barcol hardness) tests. However, D2583 was discarded as this designed for rigid plastics test produced lower band values and indicated no significant difference in hardness values obtained among all the tested samples.

Examining Shore D values (18 samples) for both inner and outer surfaces of the samples showed hardness of the inner surface (between 54.1 and 73.3) was almost always lower than the hardness of the outer surface (between 58.7 and 81.4). Some possible relationships between surface hardness and strength/modulus properties are shown in Figure 3. Hardness testing requires very small samples and is generally easily repeatable onsite. However, presence of sealing layers on liners’ inner side may contribute to producing unrealistic results and thus, potentially complicate evaluations.
11. Differential scanning calorimetry, glass transition temperature, & Raman spectroscopy

Differential scanning calorimetry (DSC) technique as per ASTM E1356 was utilized on neat thermosetting resin samples to perform thermal characterization and measure glass transition temperature ($T_g$) where resin transforms from a hard, glassy solid to a viscous liquid (Perkin-Elmer, 2000). $T_g$ values measured ranged from 76.7 °C to 129.8 °C and study showed samples with higher $T_g$ had higher flexural modulus and therefore, further investigation may help industry into resin choice phase during manufacturing.

Raman spectroscopy, which provides information about vibrational, rotational, and other low frequency transitions in molecules, was used to assess resin degree of aging and deterioration (Alam, Eklund, Allouche, & Ng, 2017). Spectra from 200 to 2,100 cm$^{-1}$ were collected on polished and cleaned 12-mm × 12-mm specimens using an R-3000 HR Raman spectrometer, which had 785-nm diode laser operating at 290-mW via fiber optic probe. Figure 4 shows the change in peaks indicating change in material properties at molecular level.

![Figure 4. Raman spectra comparison for DEN-8-1984 CIPP liner resin.](image)

The test is repeatable on retrieved samples. However, further study may help to develop a state of the art onsite instrument equipped with mini Raman spectrometer. More investigation is required to establish any correlation between Raman band shift and liner aging plus corresponding specific gravity and flexure modulus.

12. Liner buckling test

Liner buckling resistance is of interest for liner performance and therefore, resistance against the long-term buckling of CIPP under external water pressure is a key design parameter. The test was conducted only on one 30-inch long 8-inch diameter specimen, which was still too short to meet buckling test free length diameter ratio criteria to avoid any possible end effects resulting from the capping system. However, it is extremely difficult to retrieve appropriate length sample, which potentially reduces the confidence in the applicability of the results for QA/QC evaluations.

13. Conclusions

This retrospective project has provided a rare opportunity to carry out an intensive set of physical tests on CIPP liners that had been in service between 5 and 34 years. In addition to visual inspection, physical measurements and testing for flexural strength with modulus, tensile strength plus modulus, liner thickness, annular gap, ovality, specific gravity, porosity, surface hardness, glass transition
temperature, Raman band, and short-term buckling resistance provided insight in aging mechanism of CIPP liner and thus help identifying the most suitable effective tests.

**Visual inspection** remains the most important technique in the ongoing QA/QC of CIPP, although alone it does not provide all the desired information. Small distortions are not visible as cracks or offsets and leakage zones may only be visible as staining of the liner when inspections are done during dry seasons. **Flexural properties** results from this and other studies showed CIPP liners typically meet minimum values required in F1216 even after long periods in service. However, principal drawback for D790 tests were associated with sample retrieval, transportation, preparation, and testing; and current industry practice for three-point bending test (D790) language requires attention on those needed steps and ASTM subcommittee F17.67 is presently working on those comparing to D790's European counter ISO 11296-4. Moreover, D790 only provides short-term flexural properties and apparent long-term flexural modulus of the CIPP system is determined based on 10,000-h testing mentioned in D5813 and D2990; which, ironically is not mentioned in any of the above referenced standards (F1216, F1743, and F2019).

**Tensile properties** in this study was obtained for data completeness only, as condition and structural integrity of an in-service liner for a gravity sewer is more clearly represented by flexure data. However, study results revealed visible variations between the interrelationships of flexure and tensile strength-modulus and specific gravity (Figures 2 and 3).

**Thickness and annular gaps** within the host pipe are easy to carry out in retrieved samples but are typically not measurable at the site. Although thickness measurement is a very important QA tool, current practice predicts liner thickness from fabric thickness, amount of resin used, and installation pressures, but rarely actually measures in the composite final product. Difficulty of measuring thickness and annular gaps in everyday inspections suggests development of new non-destructive technologies for onsite measurement of thickness and annular gaps in cost-effective and reliable manner.

**Specific gravity, Porosity, and Surface hardness** measurements were included in this study although these are not included in a typical CIPP specifications or QA/QC procedures. The tests require relatively small samples and measurement is straightforward. In this study specific gravity was found to show some relationship to the strength/modulus (Figure 3). Most of the samples with lower specific gravity values (less than 1.10) also had the lowest flexural modulus values indicating a possible correlation and further study could make potentially useful surrogate backup quick test for assessing strength/modulus. However, for significant interpretation, the component materials and their proportions in the liner composite need to be known and based on information from a major industry contributor, use of specific gravity still requires substantial study to produce reliable enough results to abandon D790 testing on retrieved samples).

**Porosity** measurement using an MIP is not suggested to include in standard QA/QC procedure as it did not produce consistent results and it was expensive as well.

**Surface hardness** (particularly inner surface hardness) provided some interesting data that suggest possible relation to liner deterioration and aging. Flexure strength/modulus was found decreasing as the liner gets softer over time (Figure 3). At present, these relationships are considered tenuous, but the non-destructive nature of the test for in situ application and the small sample size needed in contrast to destructive test methods (D790 and D638) make further investigation of interest. Only the interior surface hardness would be able to be measured in situ but this measurement could conceivably be made by a robotic device inside the pipe although presence of sealing layers in older liners may impact measured hardness. Therefore, despite its potential as a non-destructive in situ test, more data needs to be collected to validate such outcomes.
Raman spectroscopy and DSC testing was conducted to look for evidence of CIPP liner system deterioration, but was limited in most cases due to the lack of a virgin resin sample for comparison. Thus, no specific guidance for such testing in terms of CIPP life-cycle evaluation can be provided in this study.

Short-term buckling tests provide authentic physical condition information on the aged CIPP liner but future scope of QA study is limited as specimen size, host pipe conditions, and test set-up to null end effect requires significant investment and limits the number of retrieved test samples.

This retrospective study has provided valuable information about the long-term performance of CIPP. Based on the extensive testing carried out on 18 CIPP samples ranging from 5 to 34 years in service, the study found no reason to suspect that the CIPP liners in question would not fulfill their 50-year service life predicted from lab testing (Herzog, Bennett, Rahaim, & Schiro, 2007). However, the study did identify that CIPP liners had significant variation from the design value for some basic performance parameters such as thickness and do have other defects—many of which were interpreted to have been present since the time of installation.

This paper has focused on the types of testing and evaluation that can be used to provide QA/QC on liner installation as well as track the performance of liners over time. Visual inspection and flexural testing remain the key evaluation techniques but measurement of a liner’s specific gravity and surface hardness might also be considered as a useful QA/QC procedure. Recommendations for the further development of non-destructive testing or minimally invasive testing are made so that system owners have better options to evaluate newly installed systems and to estimate the remaining life for an already lined pipe.
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