Pooled Fund Project: TRB Meeting Presentations will be delivered online with Q&A

Moderator & Pooled Fund Project Manager:
Ms. Bridget Donaldson, VDOT, Bridget.Donaldson@vdot.virginia.gov

Time: Jan 23, 2019 2:00 PM Eastern Time

Join the Meeting online or by calling in: https://zoom.us/j/150750756

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Meeting ID: 150 750 756

Find your local number: https://zoom.us/u/ab2j3Ofyty

This online meeting will involve a series of presentations by Purdue University researchers that represent their talks at the January 14 TRB Meeting in Washington, D.C. Presentation files can be found at www.CIPPSafety.org.

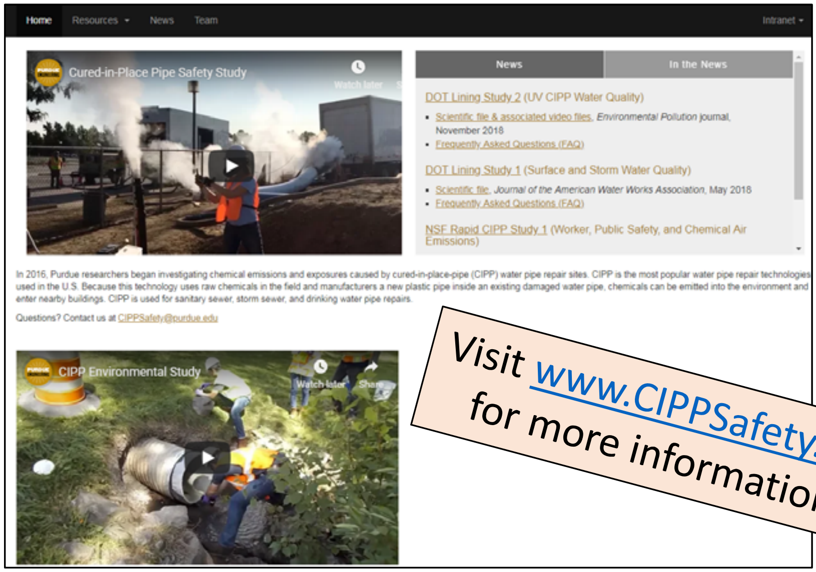
Maximize the Benefits of Culvert Lining By Minimizing Chemical Emission

Andrew Whelton

Associate Professor of Civil, Environmental, & Ecological Engineering

Understand the materials being used and emitted
Lessen the chance of safety and environmental incidents
New evidence-based recommendations for successful projects

- ✓ Educational videos
- ✓ Frequently Asked Questions
- ✓ Upgrade construction specifications
  - Employee and public safety
  - Water testing
  - CIPP testing
- ✓ Construction inspector and post-installation actions
- ✓ Learn what questions others have about these technologies



Visit www.CIPPSafety.org for more information

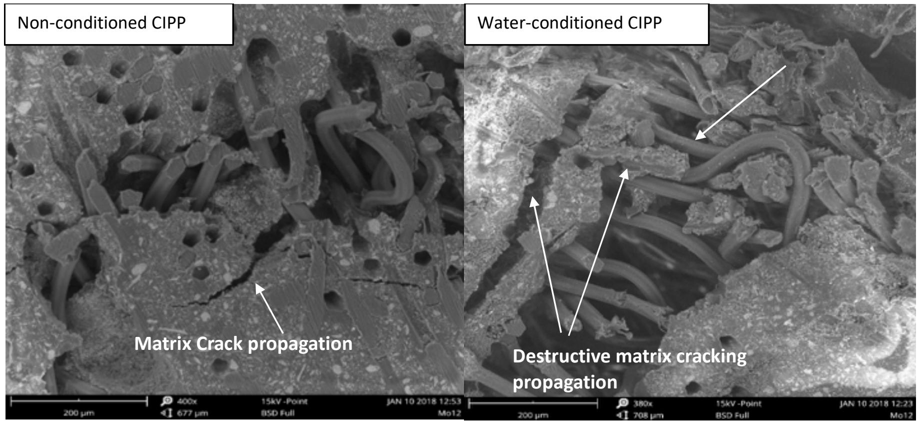
20 minutes + 5 minutes of questions

PURDUE UNIVERSITY

Plastics for Infrastructure Rehabilitation: Their Creation, Factors that Can Affect Performance, and Characterizing Product Integrity

Prof. John Howarter
Materials Engineering
Env. & Ecological Engineering
Purdue University

Prof. Jeffrey Youngblood
Materials Engineering
Purdue University



Microstructure of polymer-fiber composite used in cured-in-place pipe (CIPP) before and after accelerated aging in aqueous environments.

Visit www.CIPPSafety.org for more information

20 minutes + 5 minutes of questions

PURDUE UNIVERSITY

Evidence-Based Practices for Successful Lining Projects

Chad Jafvert

Lyles Family Professor of Civil Engineering

Andrew Whelton

Associate Professor of Civil, Env., & Eco. Engineering

Visit www.CIPPSafety.org for more information

20 minutes + 5 minutes of questions

PURDUE UNIVERSITY

Maximizing the Benefits of Culvert Lining By Minimizing Chemical Emission

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PURDUE UNIVERSITY

Jan 5, 2019 Washington, DC USA

Session 1178 *TRB Ann. Meeting*

Thank you.

Bridget Donaldson and VDOT

Jonathan Prier and OHDOT

Matt Lauffer and NCDOT

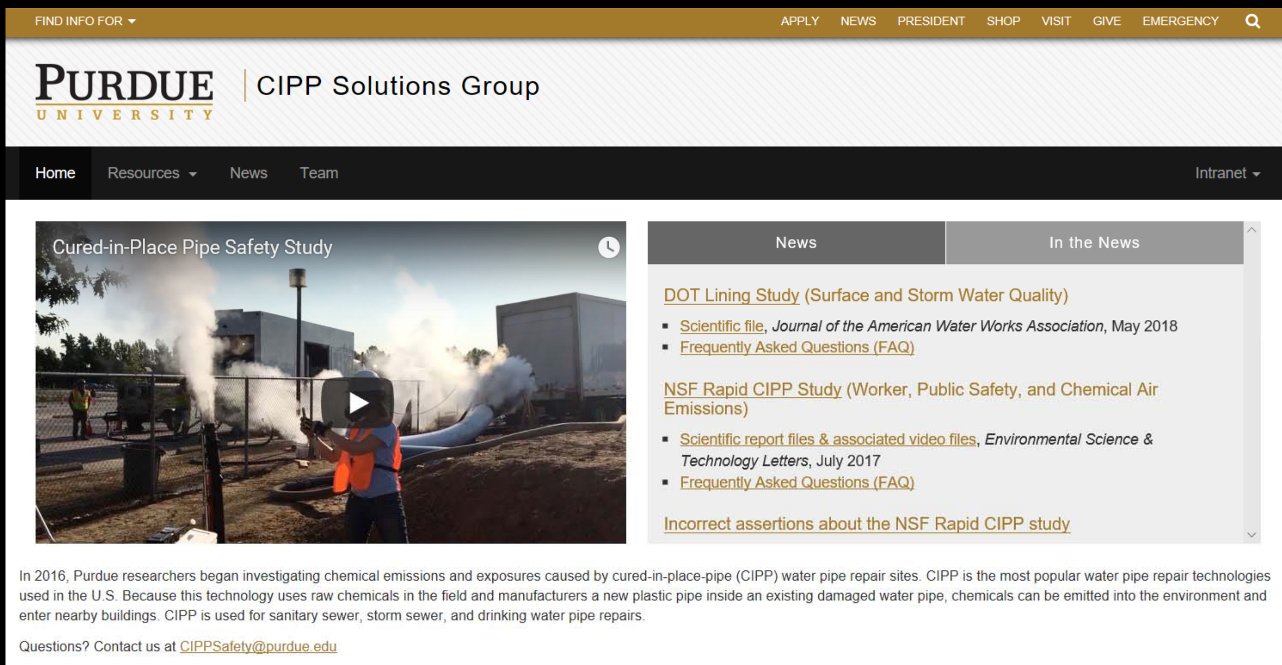
Brian Carmody and NYSDOT

John Hobelman and KSDOT

Sean Penders and CALTRANS

Standing Committee on Resource Conservation and Recovery (ADC60)
Standing Committee on Ecology and Transportation (ADC30)
Standing Committee on Hydrology and Hydraulics (AFB60)
Standing Committee on Stormwater (AFB65)
Standing Committee on Culverts and Hydraulic Structures (AFF70)
Standing Committee on Subsurface Soil-Structure Interaction (AFS40)
Standing Committee on Subsurface Drainage (AFS60)

Learn More. Freely downloadable FAQs, videos, studies, & resources at *www.CIPPSafety.org*



Presentation will be posted at www.CIPPSafety.org

Visit http://CIPPSafety.org or https://engineering.purdue.edu/CIPPSafety

Stormwater culverts and repairs in the U.S.

12 million+ linear feet of culvert in place (FHWA 2005)

Many culverts require repair

Mechanical failures can be catastrophic (traffic disruption, public safety)

Instead of replacing the damaged culvert, often trenchless culvert rehabilitation approaches can be applied

Trenchless Technology Options

Slip lining

Spiral wound pipe

Close fit pipe

Thermoformed pipe

Fold-and-form pipe

Spray-on coating

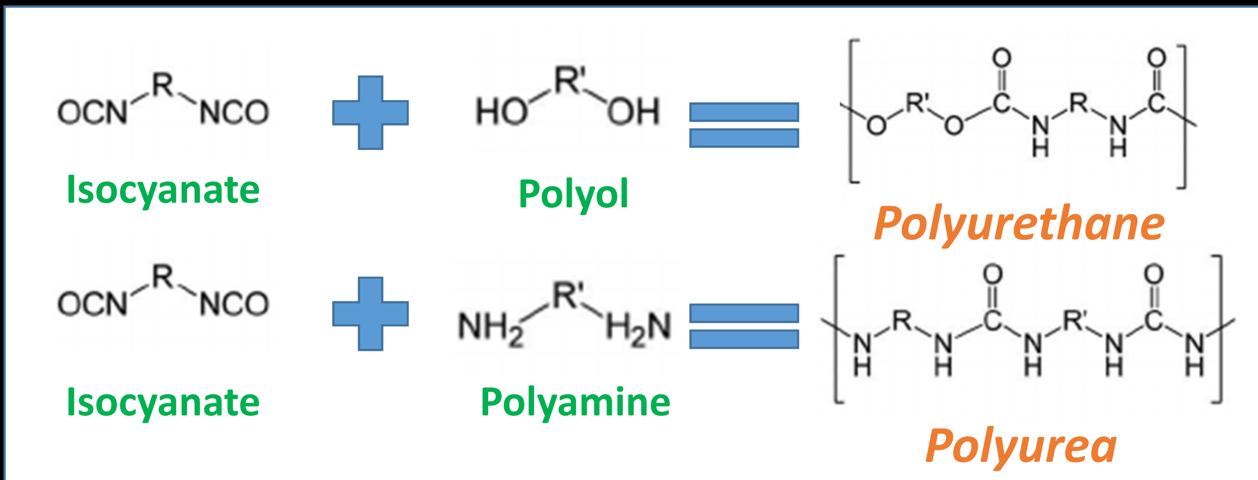
Cured-in-place-pipe (CIPP)

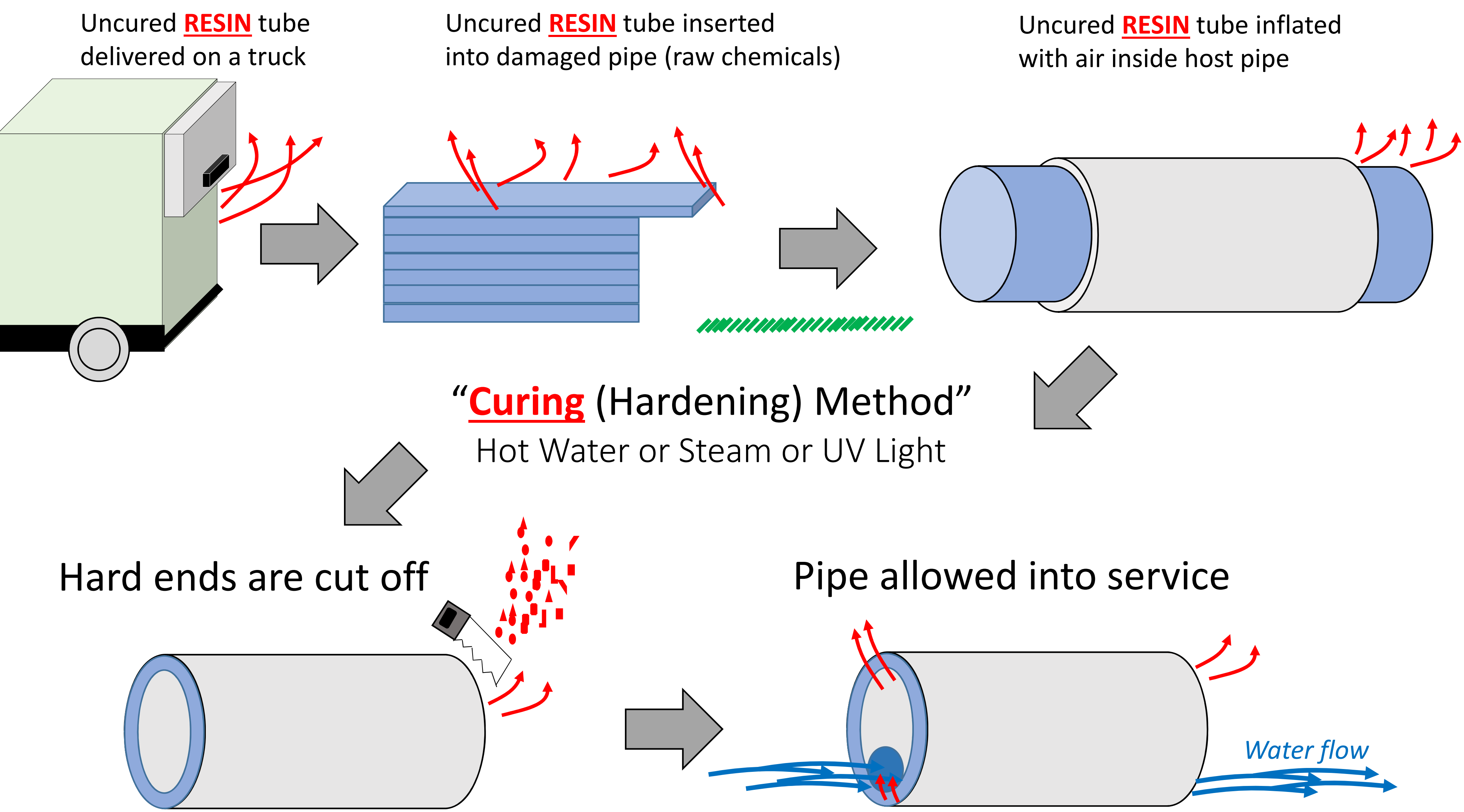
Potential Challenges for Some Options

- Water flow diversion
- Grouting necessary
- Reduction in cross-sectional area
- Structural integrity not improved
- Host pipe must be completely dry
- Cost

MAJOR DIFFERENCE: Insert Prefabricated Material vs. Chemically Manufacture Technology Onsite

Several culvert repair technologies ***chemically manufacture*** the new lining at the culvert site – Inside the Asset



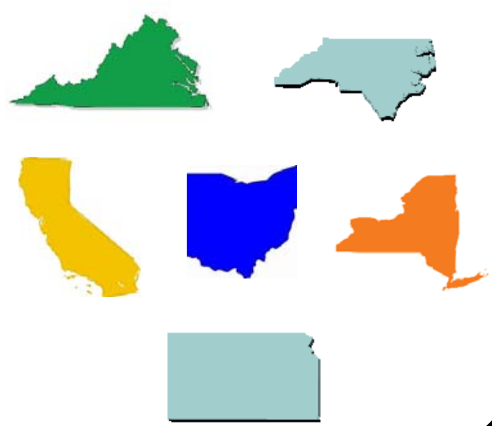

Uncured RESIN tube delivered on a truck
Uncured RESIN tube inserted into damaged pipe (raw chemicals)
Uncured RESIN tube inflated with air inside host pipe
"Curing (Hardening) Method"
Hot Water or Steam or UV Light
Hard ends are cut off
Pipe allowed into service
Water flow

POOLED FUND STUDY: Contaminant Release from Storm Water Culvert Rehabilitation Technologies: Understanding Implications to the Environment and Long-Term Material Integrity, 2016-Present

Goal: To enable DOT to make more informed decisions with regard to polymer in-situ lining method selection, specification development, and oversight.

Objectives: (1) The scope of the problem across DOTs; (2) The effectiveness of existing construction specifications at minimizing contaminant release from rehabilitated culverts; and (3) The degree to which the structural integrity and longevity of rehabilitated culverts are compromised by chemical leaching.

Our Partners



1. Critical Review: Spray-on lining chemical release
2. Critical Review: CIPP lining chemical release
3. Feedback from 32 DOTs about in-situ lining practices
4. Thermal-CIPPs: Field- and Bench-scale studies
5. UV-CIPPs: Field- and Bench-scale studies
6. Recommendations for projects and future work

Results: Critical Review of Spray-On and CIPP Lining

Feedback from 32 DOTs about their spray-on and CIPP lining practices for culverts

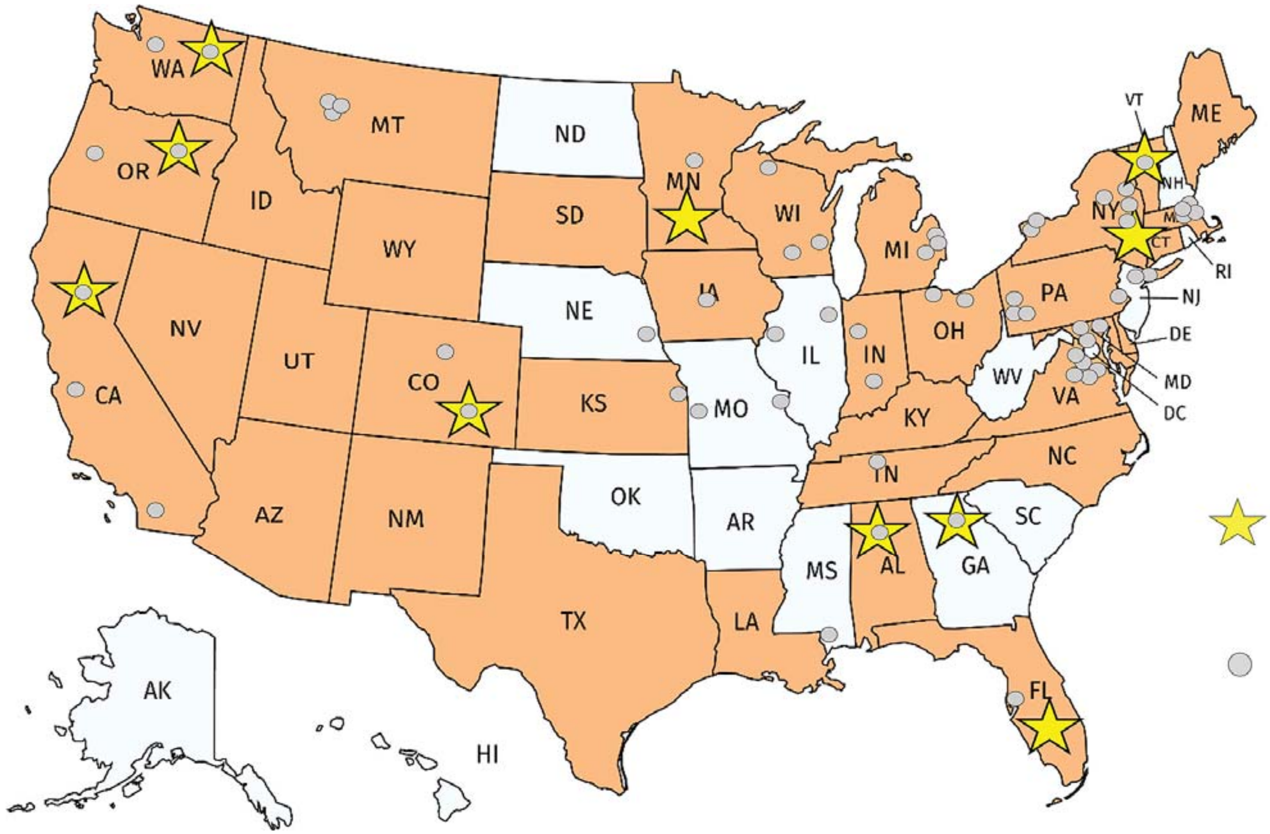
3 states have used spray-on lining methods

26 states have used CIPP methods

Only 2 spray-on lining chemical monitoring studies found in literature: No environmental contamination incidents were found for spray-on coatings, although air emission (overspray)

VDOT has the most detailed spray-on lining specifications which are based on field- and bench-scale tests

As of May 2017, CIPP Lining Use was Widespread. Waterway contamination events were also numerous.



This image only denotes some of the incidents we identified

☆	Water contamination incidents	[13]
○	Air contamination incidents	[59]

Ra et al. (2018) Critical Review: Surface Water & Stormwater Quality Impacts of Cured-In-Place-Pipe Repairs. *J. Am. Water Works Assoc.* OPEN ACCESS. https://doi.org/10.1002/awwa.1042

Some of the incidents we found:

Colorado, Alabama:	Upstream culvert repair caused downstream drinking water contamination
Vermont:	Fish kill, trout stream
Georgia:	Odors, wastewater discharge at University campus
Oregon:	“The styrene levels were so high [the] responder had to wear a respirator to collect samples”.
Connecticut:	12 days after, 0.291 mg/L styrene found downstream. *[Note: 0.005 mg/L styrene limit in some state regulations]*

Often due to contractor material handling (i.e., release of wastewater, uncured resin, condensate, or other materials) and lack of effective oversight.

Often DOTs and contractors narrowly tested waterways for styrene, but more chemicals with aquatic toxicity were emitted

Chemical levels found were much higher than what industry claims

CIPP wastewater can negatively impact wastewater treatment plants. Some have banned CIPP wastewater or set styrene limits of <2 mg/L (US), 0.4 mg/L (Germany)

Ra et al. (2018) Critical Review: Surface Water & Stormwater Quality Impacts of Cured-In-Place-Pipe Repairs. *J. Am. Water Works Assoc.* OPEN ACCESS. https://doi.org/10.1002/awwa.1042

From our review: Some CIPP ingredients (initiators) are designed to react and form new chemicals

Trigonox®
Acetone
Acetophenone
Benzene
Benzoic acid
tert-Amyl alcohol
tert-Butanol
3-*tert*-Butoxyheptane
2-*tert*-Butyloxy-24,4-trimethylpentane
Carbon dioxide
3-(1,1,Dimethylpropoxy) heptane
Ethane
2-Ethylhexanoic acid
Heptane
Methane
2-Phenylisopropanol
3,3,5-Trimethylcyclohexanone

Perkadox®
Benzene
Benzoic acid
4-*tert*-Butylcyclohexanone
4-*tert*-Butylcyclohexanol
Carbon dioxide
Diphenyl
Phenylbenzoate
Tetradecanol

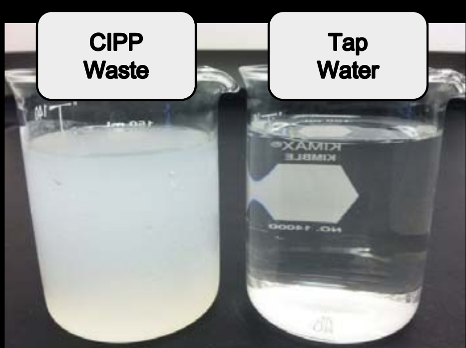
***N,N*-Dimethylaniline**
Aniline
Carbon oxides
Nitric oxides

Butanox®
Acetic acid
Carbon dioxide
Formic acid
Propanoic acid
Methyl ethyl ketone

Many are water soluble and have aquatic toxicity thresholds

Ra et al. (2018) Critical Review: Surface Water & Stormwater Quality Impacts of Cured-In-Place-Pipe Repairs. *J. Am. Water Works Assoc.* OPEN ACCESS. https://doi.org/10.1002/awwa.1042

Few Independent Studies have been Conducted



Investigator	A Few Observations
CSUS 2017 [CALTRANS]	10 steam CIPP + 1 UV CIPP; Max 0.2 mg/L styrene, other VOCs present; Contractors did not follow their submitted designs, likely stripped out chemicals that would have leached
USA 2014 [VDOT]	1 steam CIPP; 7.4 mg/L styrene in water; Waste was 36,000 mg/L COD, dissolved daphnids in 24 hr; Styrene not responsible for aquatic toxicity; Many other VOCs and SVOCs released
VDOT 2013	1 UV CIPP; 120 days after install vinylic monomer exceeded tox threshold (87 mg/L); 12 mg/L styrene found after install in water
NYSDOT 2008	4 Hotwater CIPPs; Only styrene looked for; Max. 250 mg/L in water
VDOT 2008	7 CIPPs; Only styrene looked for; Max 77 mg/L in water, 80 days after install styrene present in water

A few others not shown. Can be found in Ra et al. 2018.

It's NOT just styrene. Many compounds NOT listed on safety data sheets have been found at CIPP worksites.

Acetone
Acetophenone
Benzaldehyde
Benzene
Benzoic acid
Benzyl alcohol
BHT
2-Butanone (MEK)
tert-Butyl alcohol
tert-Butyl benzene
4-*tert*-Butylcyclohexanone
4-*tert*-Butylcyclohexanol
Chloroform
o-Chlorotoluene

Diallyl phthalate (DAP)
Dibutyl phthalate (DBP)
Diethyl phthalate (DEP)
Di(2-ethylhexyl) phthalate (DEHP)
4-(1,1-Dimethyl) cyclohexanol
4-(1,1-Dimethyl) cyclohexanone
1-Dodecanol
Ethylbenzene
3-Heptanol
Isopropylbenzene
p-Isopropyltoluene
Methylene chloride
N-Propylbenzene
Styrene

Phenol
1-Tetradecanol
Tripropylene glycol diacrylate
Toluene
1,2,4-Trimethylbenzene
1,3,5-Trimethylbenzene
Xylene (total)
And more…

Several have been found exceeding state water quality limits.

Teimouri et al. 2017. Worksite Chemical Air Emissions and Worker Exposure during Sanitary Sewer and Stormwater Pipe Rehabilitation Using Cured-in-Place-Pipe (CIPP). Env. Sci. Technol. Letters.

Industry standards, training, and textbooks *all need to be upgraded to limit health and environmental repercussions of using lining technologies*

- Construction Inspectors course lacks training about water quality impacts, methods to detect them or evidence-based practices to avoid them

- Industry Styrene Resin Handling Document (old versions and 2018) have numerous incorrect statements, that guidance may prompt Clean Water Act violations and greater safety risks to workers and the public

  11 years ago NYSDOT noted some similar questions about information contained in that document

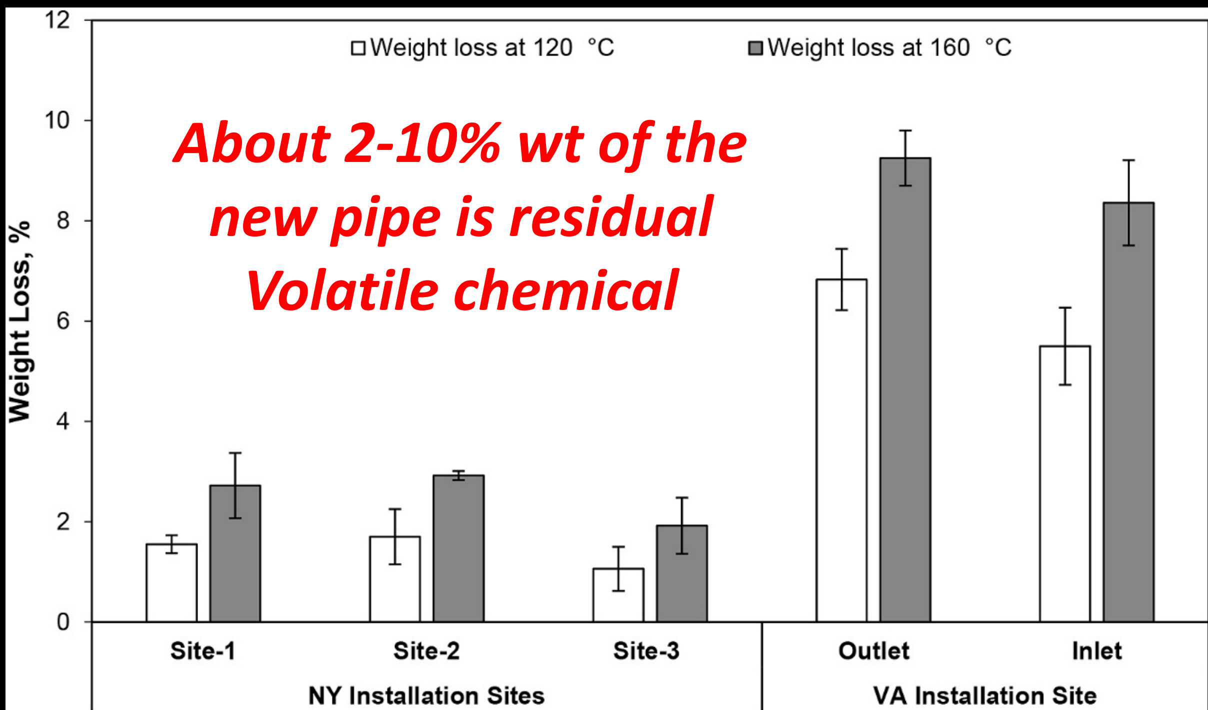
Feedback Received: Most DOTs Did Not Have Specification Requirements to Characterize or Limit Chemical Release

Requirement	States that Use CIPP
Before construction	
Obtain and show POTW permit to the engineer	4 of 16
Install impermeable liner up and downstream	4 of 16
Conduct water testing at the site	4 of 16
Before reinstating flow	
Rinse new liner with clean water, capture, and dispose	5 of 16
Prohibit return to service before a min. unspecified period	4 of 16
Prohibit return to service before a min. period (2,4,7 days)	3 of 16
General requirements	
Capture and dispose of compounds, water, and condensate	10 of 16
Conduct water testing at site	4 of 16
Contractor is responsible for reporting any water quality alterations	3 of 16

Our new water study: 4 UV CIPPs, 2 states

- A Few Field Observations
  - Glide sheet can limit raw chemical contact with ground
  - Encapsulation may limit raw chemical release
  - Particulates with chemical residual released during cutting
  - Workers may contaminate water/soil with resin on gloves, boots, etc.
- A Few Laboratory Observations
  - All chemicals of environmental concern not disclosed on MSDS
  - Particulates loaded with leachable chemicals
  - Magnitude of residual in the new CIPPs differs a lot
  - CIPPs contain residual that can leach out post-installation

Li et al. 2018. Outdoor manufacture of UV-Cured plastic linings for storm water culvert repair: Chemical emissions and residual. *Env. Pollution.* https://doi.org/10.1016/j.envpol.2018.10.080



Pinch of salt = 148 mg

Pinch of CIPP dust = 100 mg caused 4-16 mg/L styrene in water in 24 hr

Li et al. 2018. Outdoor manufacture of UV-Cured plastic linings for storm water culvert repair: Chemical emissions and residual. *Env. Pollution.* https://doi.org/10.1016/j.envpol.2018.10.080

Our new water study: 5 Thermal CIPPs, 2 states

- A Few Field Observations
  - Visible emissions into air
  - Multi-phase mixture: Solids, liquids, gases emitted into air (Plume is NOT STEAM)
  - Particulates released during cutting
- A Few Laboratory Observations
  - All chemicals of environmental concern not disclosed on the MSDS
  - Contractors cross-contaminated non-styrene CIPP with styrene
  - Magnitude of residual differs across CIPPs
- CIPPs contain residual that can leach out post-installation

Ra et al. Coming Soon.

Observations

- There are major issues but these can be resolved: water, waste, air, worker safety, residential safety, best manufacturing practices, good housekeeping
- Unclear scale of spray-on lining impacts, technologies used much less than CIPP
- MSDSs do not explain the entirety of chemicals for environmental or safety concern for lining activity. That's not their purpose. Resin contaminants, byproducts and undisclosed ingredients not mentioned.
- Wastes are a problem: Condensate, wastewater, particulates.
- Require water testing before and after installation.
- Do not permit reinstatement until test shows no impact.

There's an opportunity for improved use of lining methods so projects and impacts end when the contractor leaves the site….not continue.

Thank You

Andrew Whelton, Ph.D.

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Maximizing the Benefits of Cured-in-Place Pipe Stormwater Culvert Rehabilitation with Environmental and Safety Considerations

Prof. John A. Howarter[1,2] and Prof. Jeffrey P. Youngblood[1]

[1]School of Materials Engineering

[2]Environmental & Ecological Engineering

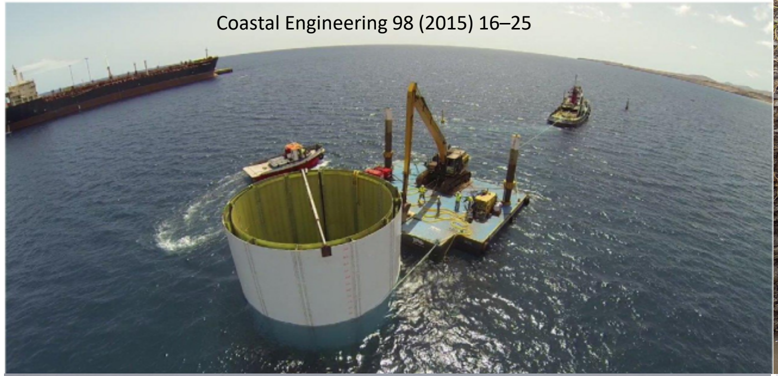
Purdue University

January 14, 2019

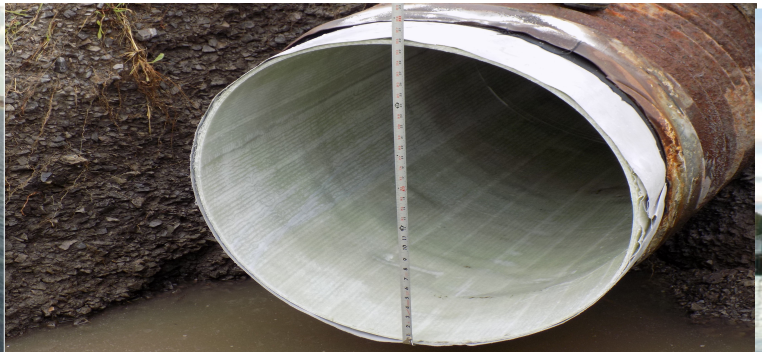
Transportation Research Board Annual Meeting

Session: Plastics for Water Infrastructure Rehabilitation: Their Creation, Factors That Can Affect Performance, and Characterizing Product Integrity

A Primer on Fiber Reinforced Polymer Composites



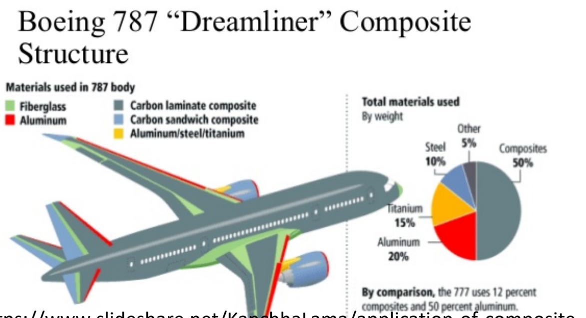
Coastal Engineering 98 (2015) 16–25



https://www.tes.com/lessons/pcQxUYMrDAPjKw/bridges

http://www.kcautoacc.com/AUTOart-76027-McLaren-P1-Matt-Black-with-Red-Accents-118-Scale-Composite-Car-_p_18280.html

http://www.shridhanalakshmi.com/wind.php



https://www.slideshare.net/KanchhaLama/application-of-composite-materials-in-aerospace-industry-1?next_slideshow=1

http://www.luxury
compos

https://www.usatoday.com/story/news/nation-now/2016/02/24/army-combat-shirt-body-armor-2019/80851048/

http://www.onur.net/en/references/mobile-air-traffic-control-towers-project-for-turkish-airforce-8/

What are fiber reinforced polymer composites (FRPCs)?

- Composites materials are made by combining two materials where:
  - ❖ One of the materials is a reinforcement (fiber)
  - ❖ The other material is a matrix (resin).
- Fibers: glass fiber (fiberglass), carbon fiber, aramid, and polyester.
  - The fibers come in veil mat, short fiber mat, woven cloth, unidirectional tape, biaxial cloth or triaxial cloth.
- Resins: Typically thermoset resins such as polyester, vinyl ester, epoxy, polyurethane and phenolic.
  - The resins start as a liquid and polymerize during the cure process and harden.

FRPCs are high performance materials that are much higher cost than other structural materials

However, in construction, FRPCs have been considered as substitute for traditional civil engineering materials, namely concrete and steel.

This because FRPCs are:

- Lightweight and non-corroding (polymer based)
- Exhibit high specific strength and specific stiffness (due to fibers)
- High durability (due to matrix)
- Can be tailored to satisfy performance requirements
- Are easily constructed, therefore cheap for low run size

Formula cars vs production cars!

Fiber type is dependent upon many factors

Aramid/UHMWPE

- Advantages: Moderate strength, High stiffness, Low density, High toughness
- Disadvantage: SUPER high cost, Difficult to bond

Carbon Fiber

- Advantages: High strength, High stiffness, Low density
- Disadvantage: High cost, Brittle

Glass Fiber

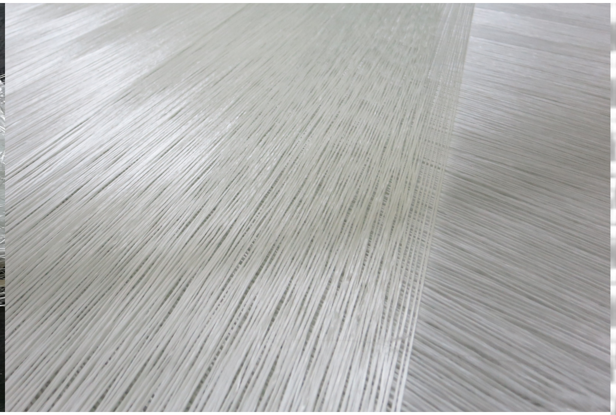
- Advantages: Low cost, High strength, Moderate stiffness,
- Disadvantage: High density, Low fatigue resistance, Stress corrosion, brittle

Staple Polymer

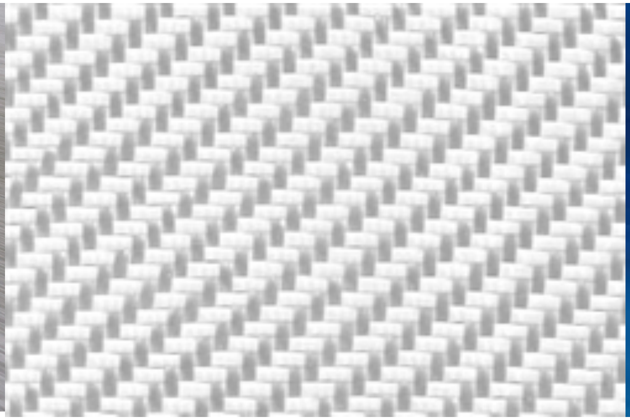
- Advantages: Extremely low cost, High toughness, Low density
- Disadvantages: Low stiffness, Low strength, low temp, poor solvent

https://www.alibaba.com/showroom/concrete-fiberglass-chopped-strand.html

http://vectorply.com/reinforcement-fibers/



https://www.uscomposites.net/ProductDetails.asp?ProductCode=FG-7725-38-10



https://www.lih-fe.com/en/product/S-glass-fiber-needle-mat-850C/fiberglass_needled_mat-004.html

Fiberglass represents > 90% of the reinforcements used in infrastructure applications

While fibers are the focus for properties, there are many possible resins that also dictate performance

Unsaturated Polyester

- Cheapest resin
- Multiple types (Ortho- vs Iso-)
- Thermal (peroxide), Redox (MEKP), or UV (Irgacure) radical cure
- Good water performance

- Safety Issues:
  - Diluted 30-60% in reactive solvent (styrene)
  - Some initiators are explosive
  - Can be composed of Phthalates

Vinyl ester

- More expensive than UPR
- Better performance than UPR
- Thermal (peroxide), Redox (MEKP), or UV (Irgacure) radical cure
- Good water performance

- Safety Issues:
  - Diluted 30-60% in reactive solvent (styrene)
  - Some initiators are explosive
  - Has BPA

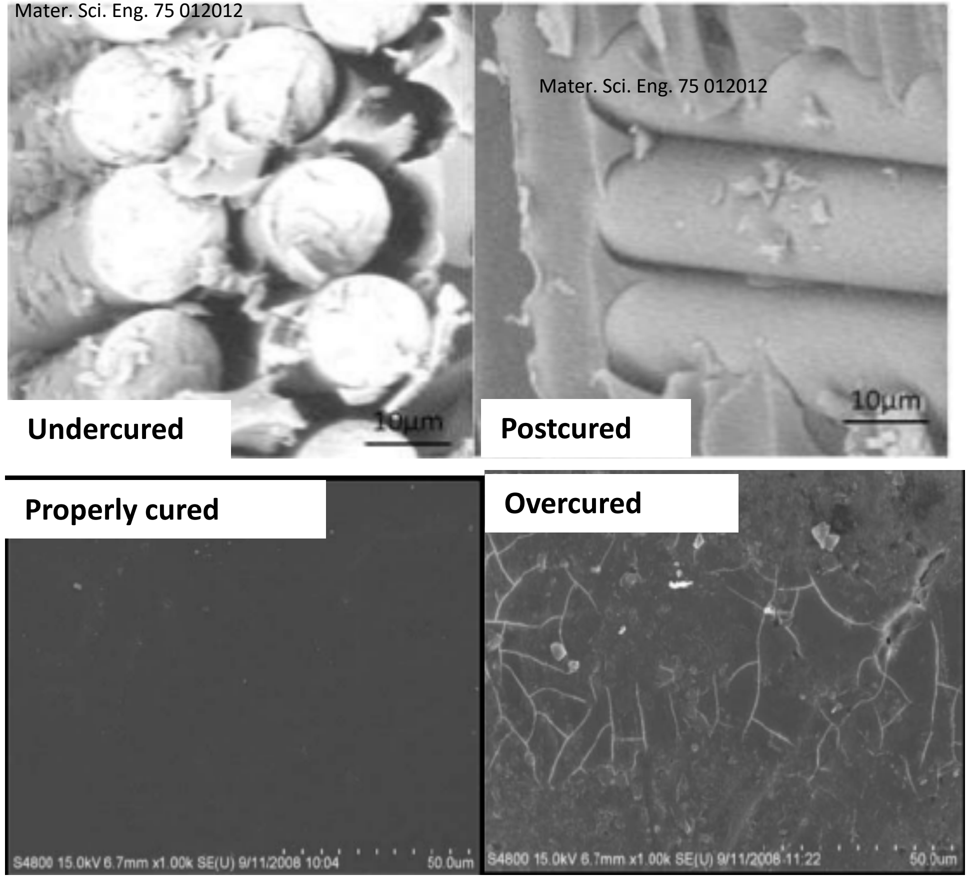
Epoxy

- Most expensive
- Best performance
- No reactive solvent
- Many types (BPA, BPF, CA)
- Can have poor water performance

- Safety Issues:
  - Has BPA
  - Can contain amines (hardeners)

Curing issues in FRPC

- The curing process plays a major role in achieving the final mechanical properties
- Aerospace industry has complicated time/temperature/pressure profile to reduce porosity and improve cure
    - Increases crosslink density, so T_g and strength increases
    - Can post-cure to improve properties
- Many possible issues with curing
    - Undercuring: Lack of complete reaction. Lowers Tg and strength and leaves residual monomer
    - Overcuring: Causes chain-scissioning, matrix cracking and debonding at fiber/matrix interface. Lowers Tg and strength. Similar to UV exposure.
    - "Overtemp" (not a real term): can heat too high
        - Thermal runaway
        - Flash off monomer (styrene)
        - Cause too fast initiator (catalyst) decomposition



http://etd.fcla.edu/CF/CFE0002406/Tipton_Bradford_R_200812_MSME.pdf

Trying to speed up curing, or "force" complete cure will cause issues – If hot is good, hotter is not better!

Why does all this matter?

Emissions and Performance

There are "free" small molecules in FRPCs after curing

- Impossible to achieve 100% cure in a thermoset
  - Highly dependent upon cure temperature, schedule and type
- Residual organic compounds will be leached out over time and may change mechanical properties of the composites.
  - Monomers such as amines (for epoxy resin), and styrene (for unsaturated polyester or vinyl ester resin) remain unreacted due to diffusion limitations
    - Composites will change properties over time and pick up water as monomer leaves.
  - Plasticizers and additives such as butylated hydroxytoluene, 1-tetradecanol, diethyl phthalate are used to impart specific properties of the composites.
    - Composites will become embrittled over time as additives are depleted.
  - Oxidation and degradation products of monomers, polymers, and initiators/catalysts remain.
- Commonly 1-6% residual monomer in UPR/VE
  - Quick calculation: L=10m, D=1m, T= 10cm, 50% resin, 1% residual monomer = ~14Kg
  - However, after initial burst from surface, monomer comes out over years.

CFRP production can pose issues to fabricators

- Three main areas of concern: fiber handling, cutting/sanding, and resin use
- Fiber handling: mostly fiber skin penetration
- CFRP cutting: breathable dust, eye irritation.
  - 2016: “OSHA Issues $47k in Penalties to Manufacturer of Fiberglass Boats For Exposing Georgia Employees to Serious Hazards” (Hansford Lawfirm)
- Resin Use:
  - Exposure to monomers (styrene from vinyl ester and polyester)
  - Environmental emissions (VOC)
  - Flammability concerns (redox initiators and brass/steel fittings, etc)

Styrene emissions were a huge issue for bathtub and boat manufacturers

- Large scale FG manufacturers were forced to change procedures due to lawsuits and regulations
  - OSHA, EPA, DHHS all issued reports regarding styrene release
- Possible solutions:
  - Industrially, proper ventilation, such as a push/pull ventilation system is necessary to remove styrene from the work area
    - Lasco Bathware $2M investment 2008 to meet clean air standards (reduced emission by ~250,000 tons/year)
  - High transfer efficiency spray guns for gel coating applications
  - Reduced styrene content in resin
  - Styrene substitution with a less volatile monomer, such as p-methyl styrene
  - Vapor suppressant
- Controls reduce exposure below threshold limits, still concerns about chronic exposure

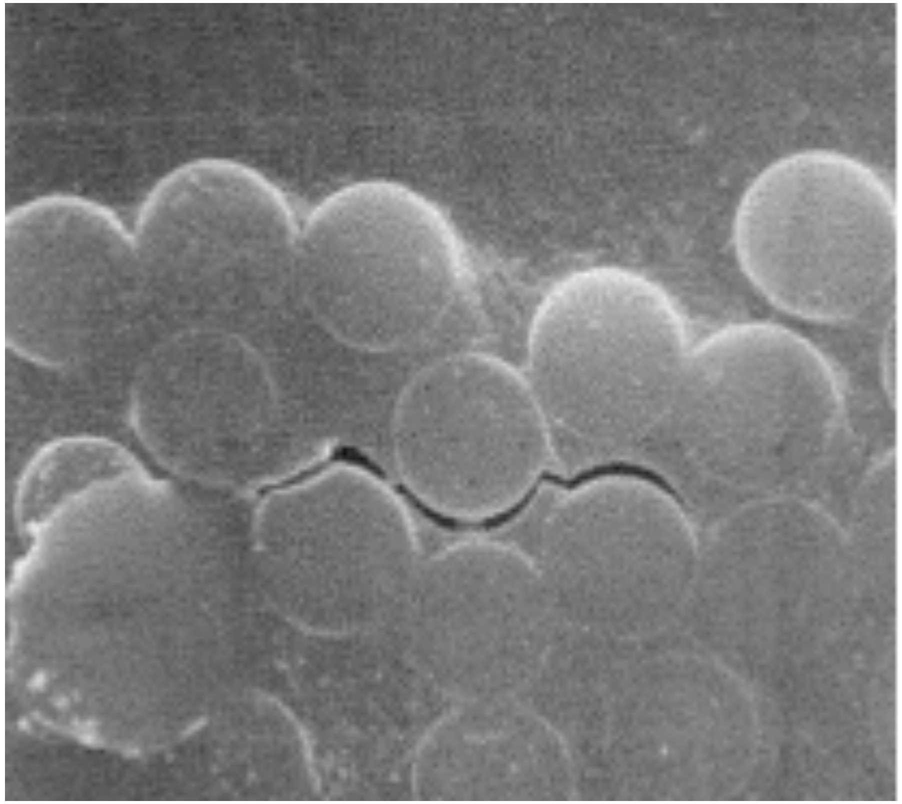
1. Industrially, ventilation/emissions control is necessary
2. Proper PPE are needed (especially for small fabricators)

What about Performance?

- There is a difference between manufacturing defects and aging (not discussing physical assaults such as earthquakes, etc)
  - Manufacturing defects are typically related to curing but can also be too much resin bleed, porosity, pinholes and poor interlaminar adhesion.
    - Poor curing will weaken material, but even if fully cured, poor interlaminar shear strength can cause failure under load.
  - Aging is also possible – polymers (such as composites) gradually lose properties in the environment.
    - Chemical attack- solvents but also water.
    - Oxidative – thermooxidative (ie time) and photooxidative (light)

In CIPP, chemical attack is most likely by Water

- Hygrothermal aging of composites can be important in wet environments
  - Water molecules diffuse into composite
    - Depends on hydrophobicity of resin and residual monomer that is leached out
  - Moisture can
    - increase creep and relaxation
    - induce stresses causing interlaminar failure
    - degrade polymers, fibers, and fiber/matrix interfaces
    - Moisture can accelerate fatigue degradation of composites,
    - Moisture can initiate localized cracking of matrix.
  - pH and Salinity can have an effect
    - Acid, Base and Salt tend to accelerate degradation
    - Contact with decaying organic matter, concrete pore solution and deicing salts may be a problem over the long term



Construction and Building Materials 48 (2013) 360–370

Oxidative aging is typically seen in "old" materials

- Rubber "dry rot", cracking of vinyl, breakage of plastic in light fixtures, yellowing of finishes near windows, etc, are all examples of oxidative aging.
- Oxidation causes chemical changes, chain scissioning, and cross-linking leading to weakening, embrittlement and discoloration.
- Highly time dependent but accelerated by heat, oxidants and light
  - In typical exterior environments, photoxidation is main culprit
  - Photooxidation depth is dependent on transparency of material
  - Most resins use a complex package of antioxidants/photostabilizers to extend lifetime

Photo of a Nylon bag under a deck for ½ summer showing light induced aging

Main take-homes for Aging

1. Time always wins!
   - Not a question of if aging failure will happen, but when.
2. Aging can be long process (years to decades) so it is hard to test for
   - So we use Accelerated Aging
3. Accelerated Aging is highly system dependent (depends on material, application (conditions), time-scale, and model used.
   - There are >2000 ASTM standards for Accelerated Aging in polymers!
4. Vini, Vidi, Validation.
   - Need validation against real world/real time performance.

Overall, there is a general lack of peer-reviewed public aging studies on CIPP

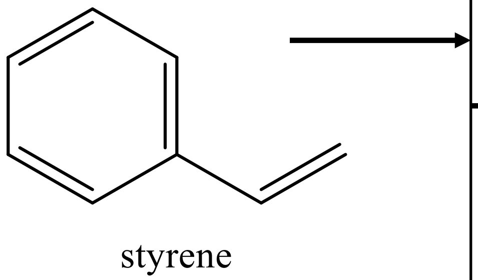
What about our results?

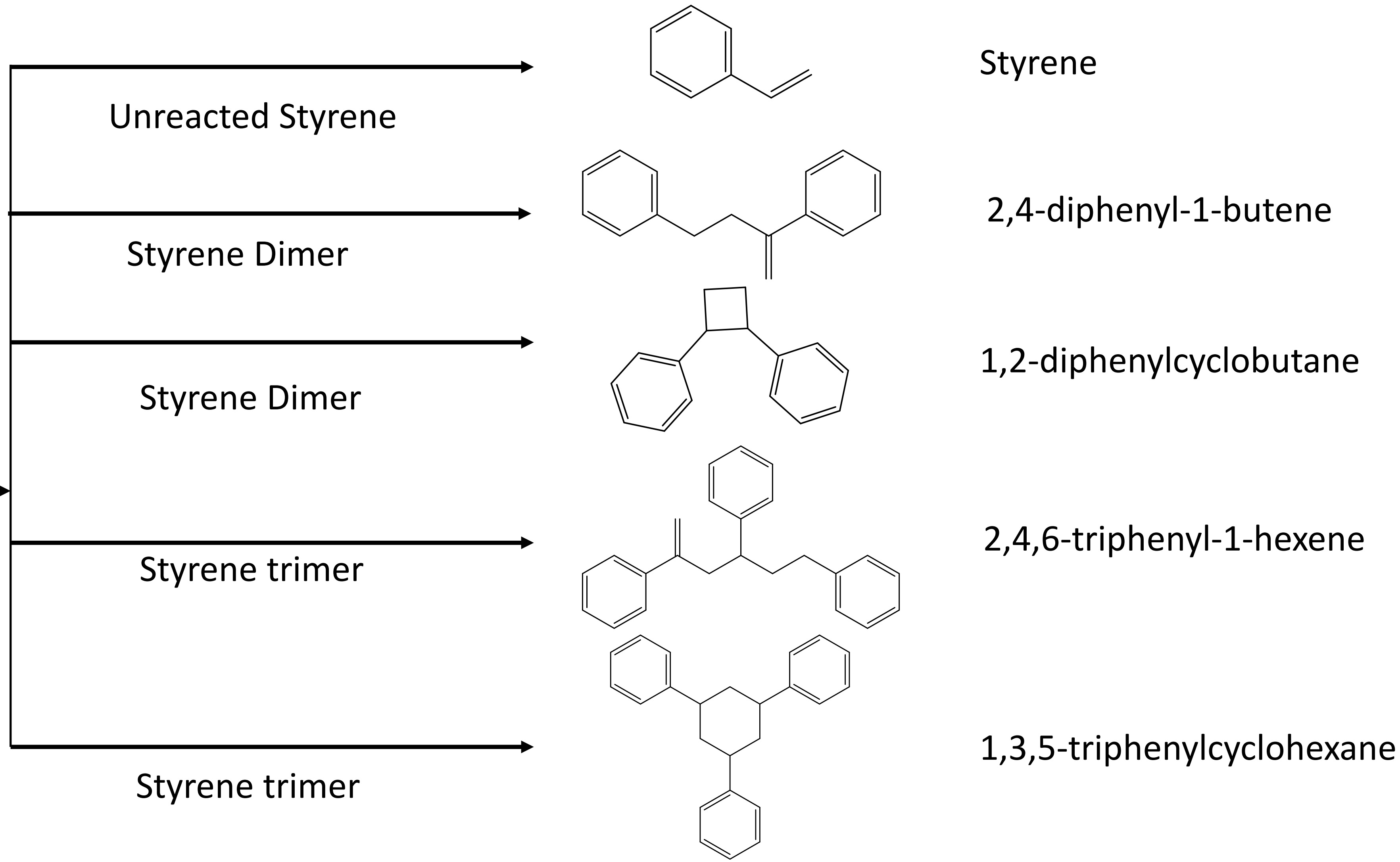
Key Materials Characterization Techniques

- **H-NMR**: Identifies the leachable chemicals from cured CIPP
  - Used as secondary validation of mass-spectrometry
- **Differential Scanning Calorimetry (DSC):** Curing exotherm, crystallization and melting of CIPP components
- **Thermogravimetric Analysis (TGA):** Determination of percentage of volatile compounds and degradation behavior of CIPP
- **Optical / electron microscopy:** Quantify porosity, morphology changes, assess fracture damage after mechanical testing
- **Mechanical testing:** Interlaminar shear strength, flexural strength, modulus, toughness via three point bend test.

Predicted Compounds From Styrene monomers

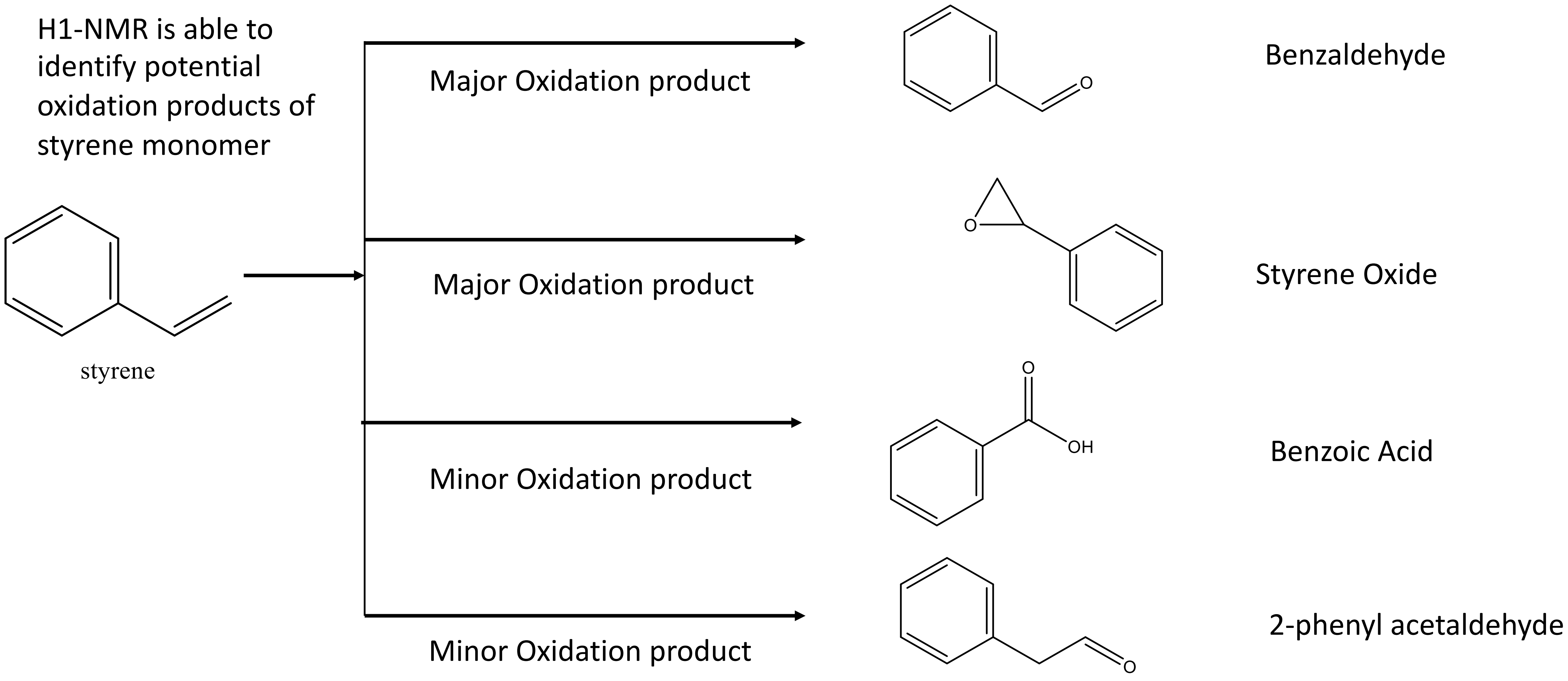
Aborted reactions of the styrene polymerization can result in dimers, trimers and oligomers of styrene which were present in H1-NMR but not necessarily part of the reported materials list as **these compounds are created in-process**





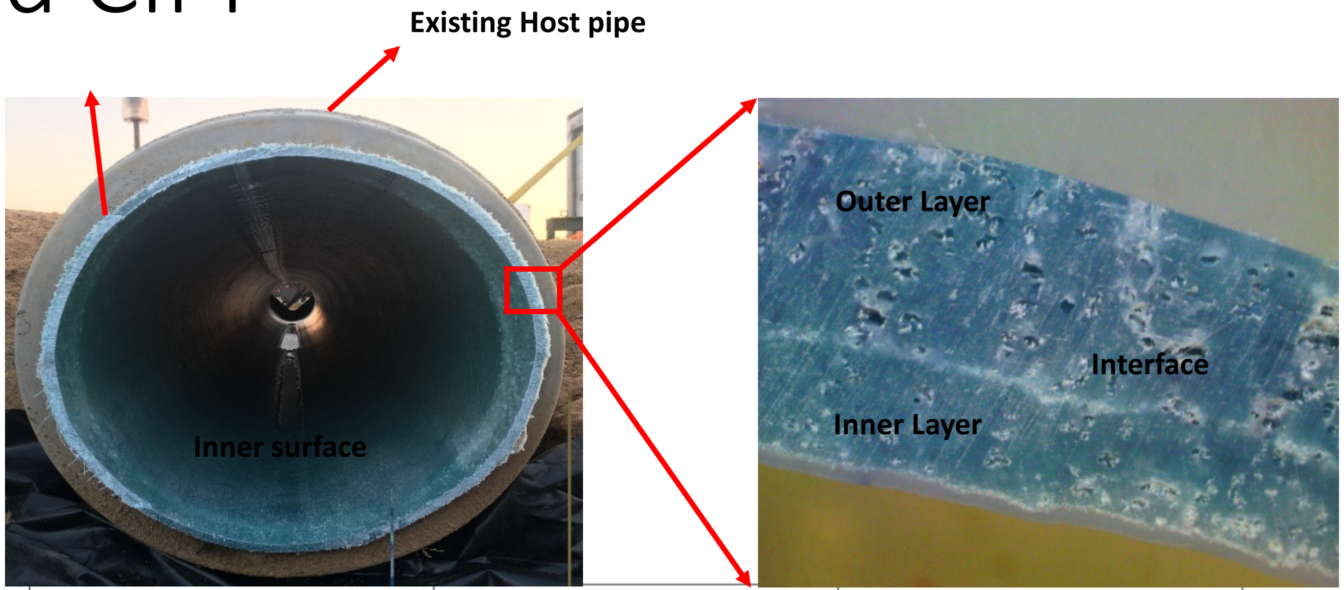
Predicted Compounds From oxidation of styrene

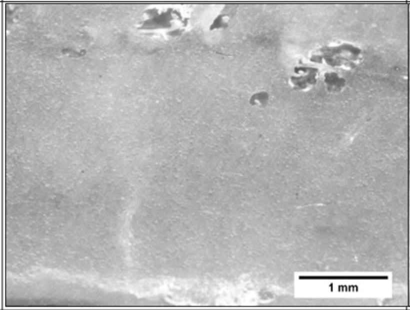
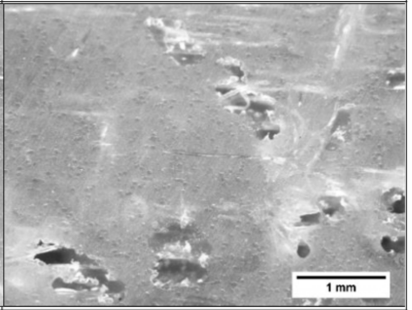
Styrene which does not successfully polymerize can also **oxidize in the hot steam environment.** H1-NMR is able to identify potential oxidation products of styrene monomer



Porosity of Steam Cured CIPP

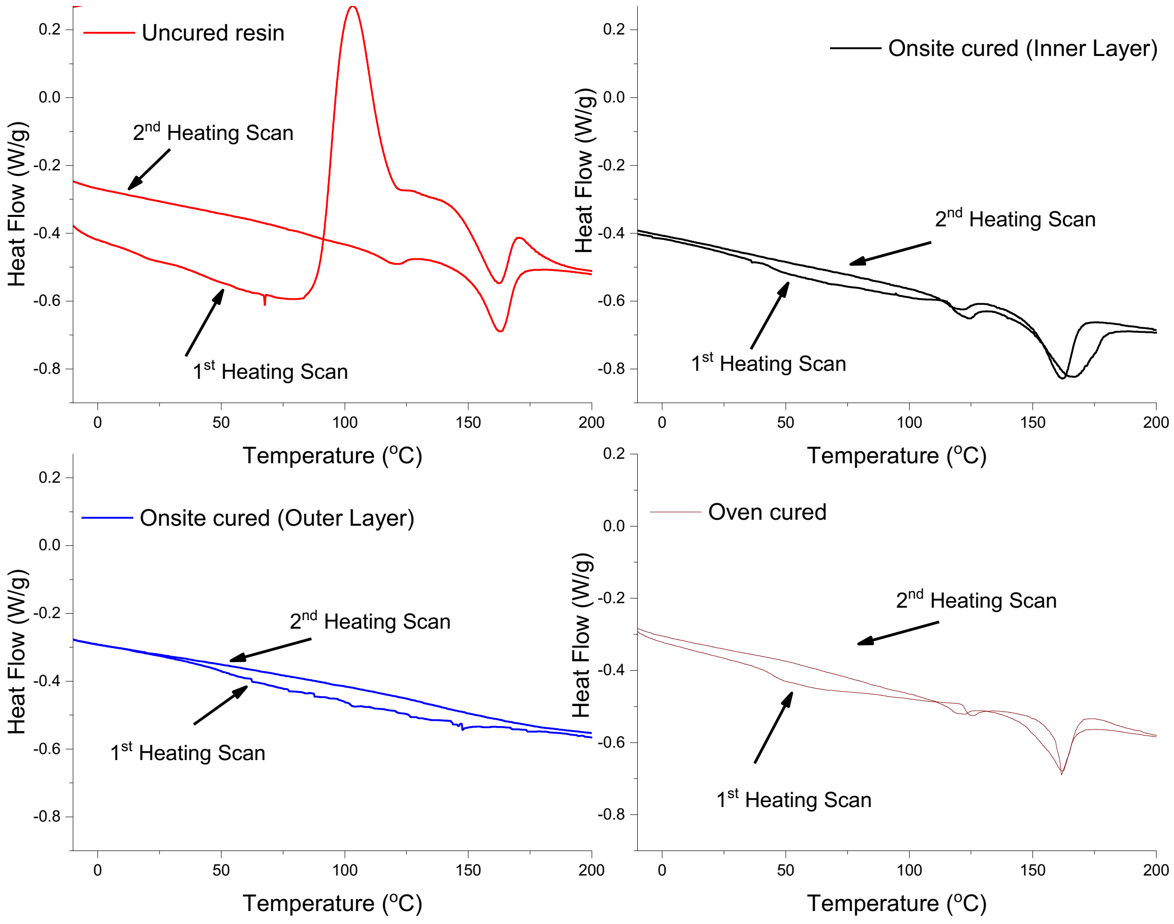
- During installation, the edge of outer layer experiences lower curing pressure and temperature than inner layer.
  - The porosity was diffusing from the inner layer to edge and coalesced together to form large cylindrical shape porosity.
- The processing pressure was not high enough to diffuse the porosity or air bubbles out of the CIPP liners.
- Porosity of Outer layer is much higher than Inner layer



Properties	Inner Layer	Outer Layer
Surface Morphology		
Porosity, %	3.41 ± 0.89	8.07 ± 1.32
Density, g/cm^3	1.24 ± 0.02	1.23 ± 0.01
Thickness, mm	2.65 ± 0.05	5.26 ± 0.09

DSC (degree of thermal cure)

- DSC indicated that the onsite-cured and laboratory cured specimen were effectively equivalent
- All specimen had small but detectable amount of uncured/volitile material.

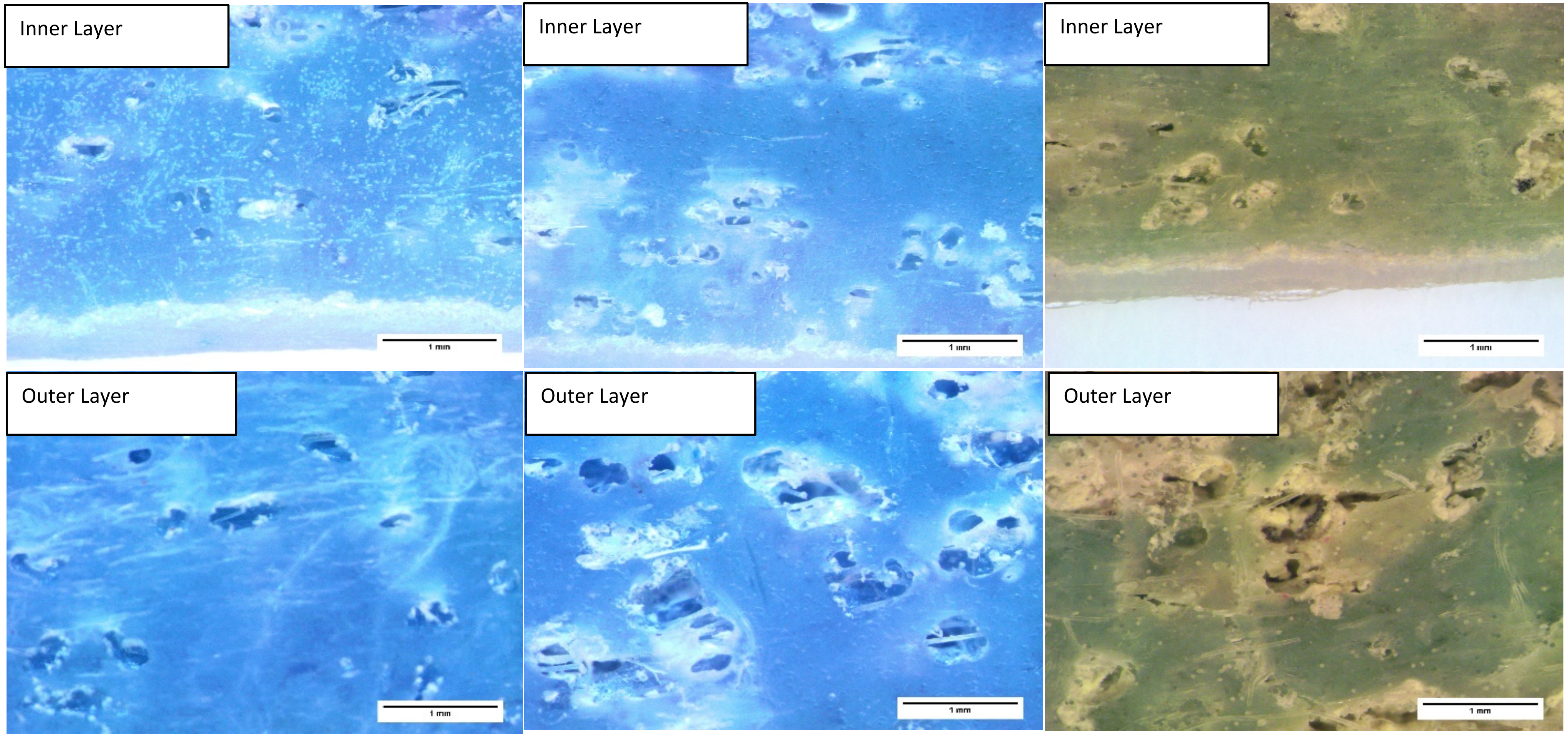


TGA of uncured, onsite-cured, and oven-cured CIPP liners

Sample	Weight loss at 120 °C (%)	Weight loss at 160 °C (%)	1st step Decomposition Temp (°C)	2nd step Decomposition Temp (°C)	3rd step Decomposition Temp (°C)	Residue Content at 900 °C (%)
Uncured liner	7.73±0.18	9.16±0.33	373.6 ± 0.8	412.44 ± 0.30	528.30±0.56	24.74±0.75
Oven-cured liner	0.42±0.11	1.41±0.29	381.8 ± 0.48	410.21 ± 2.52	532.29±0.51	25.44±0.82
Onsite-cured (Inner layer)	0.47±0.03	0.80±0.06	379.95 ± 0.47	403.11 ± 8.51	528.83±3.78	15.95±1.27
Onsite-cured (Outer Layer)	0.53±.03	1.63±0.21	381.84±.48	420.6 ± 0.48	530.25±1.42	26.40±.82

- Outer layer had 2x volatile weight loss at 160C compared to inner layer. Indicating that volatile content may be related to measured porosity.
- Onsite-cured material had volatile weight loss to a similar degree as oven-cured liner
- Any sorbed water will leave system at 120C step. Difference between 120 and 160 weight loss is attributed to volatile organic content (VOC) (i.e. unreacted monomer which is mobile within the material)

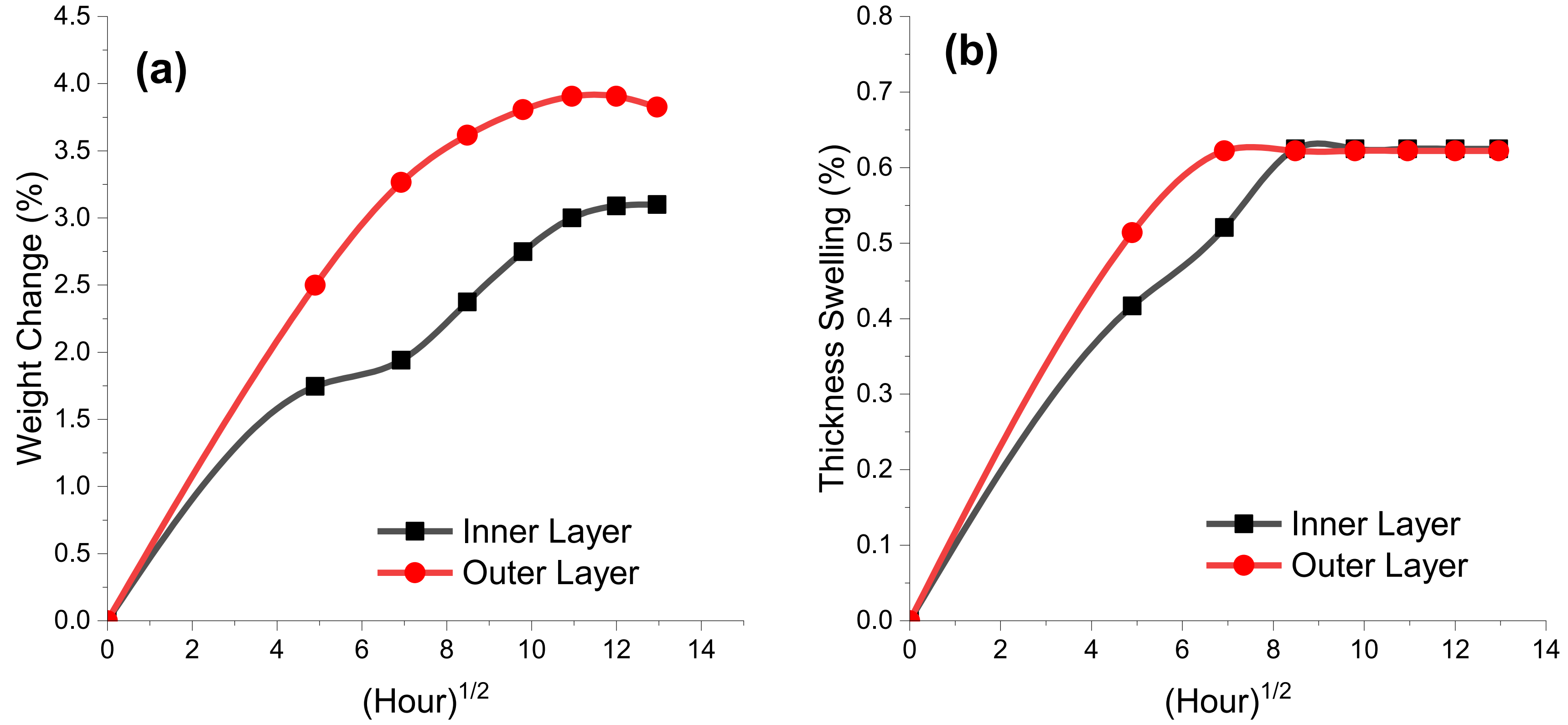
Conditioning with water or solvent increases porosity, but overall more porosity in outer layer



Non-conditioned **Water conditioned** **Chloroform conditioned**

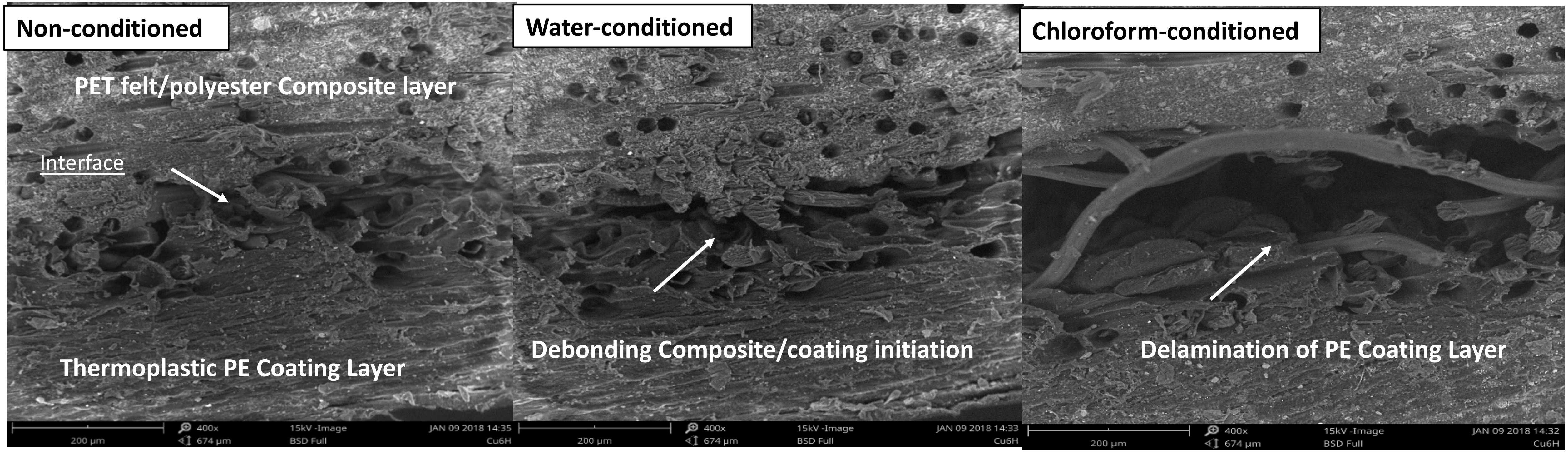
Exposure to water or solvent clearly removes some material

Weight (a) and thickness (b) change of inner and outer layers of CIPP as a function of immersion time in water.



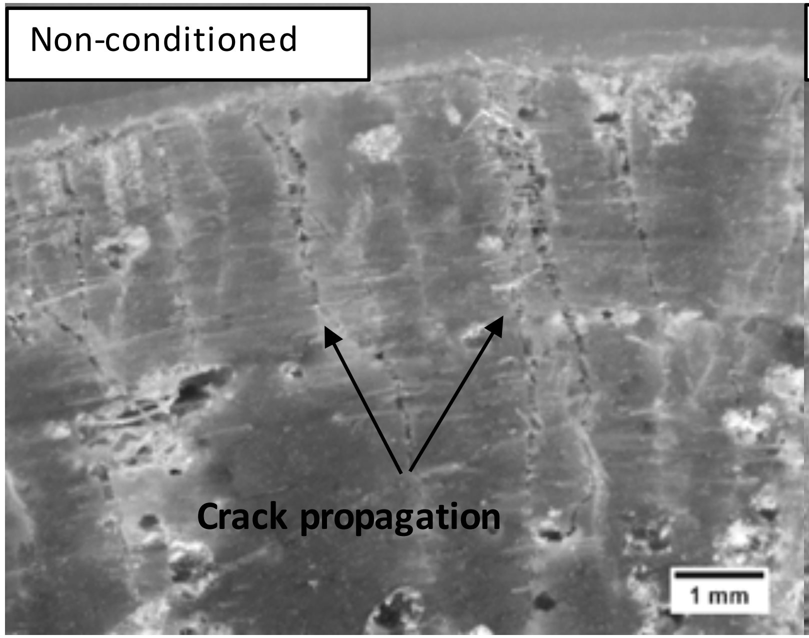
- Outer layer (higher porosity) is able to sorb more water (up to 4% by weight).

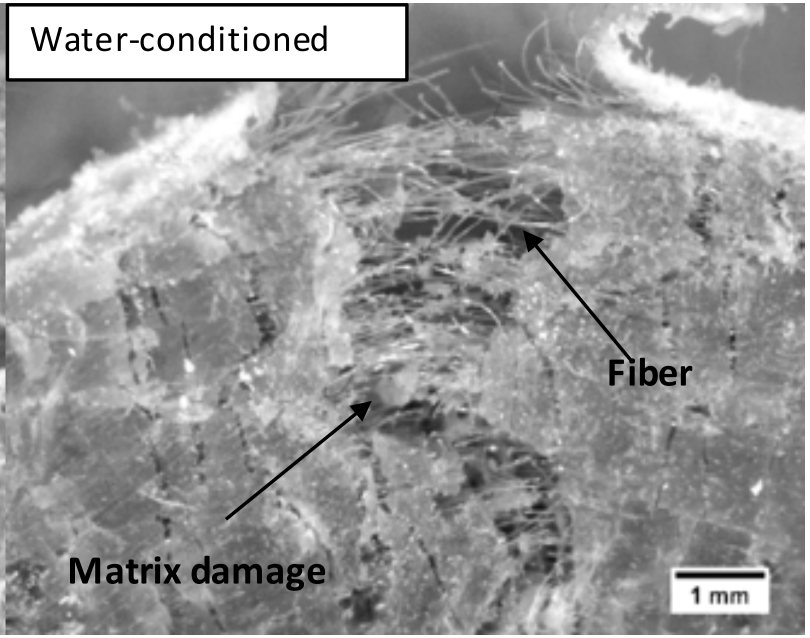
Composite/Coating middle-interface experienced severe damage upon conditioning

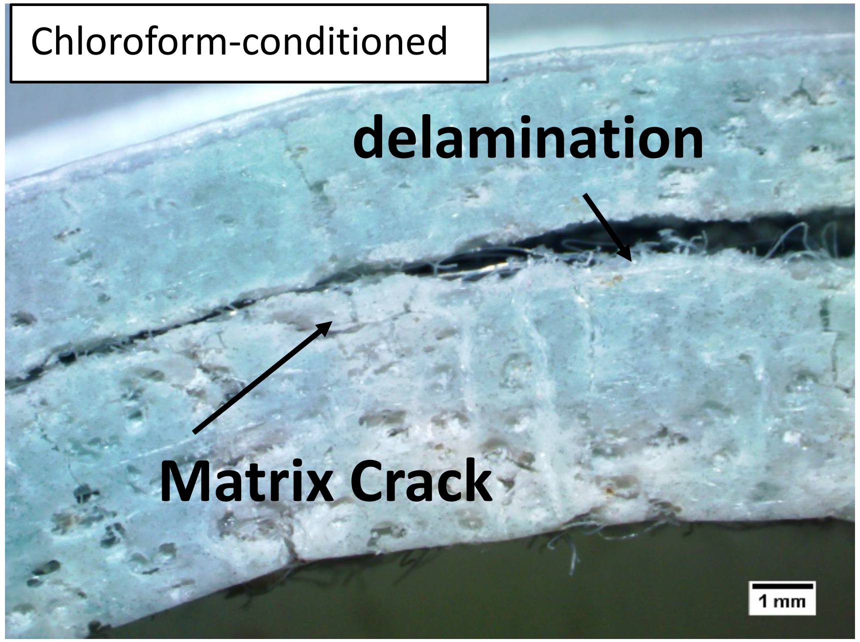


Chloroform sorption induces much higher internal residual stresses which initially weakening the bond between the composite and coating layer, and finally delaminate the interface coating from the composite layer (see interface on prior slide between 'inner' and 'outer' layer.

Different failure modes happen in conditioned specimens





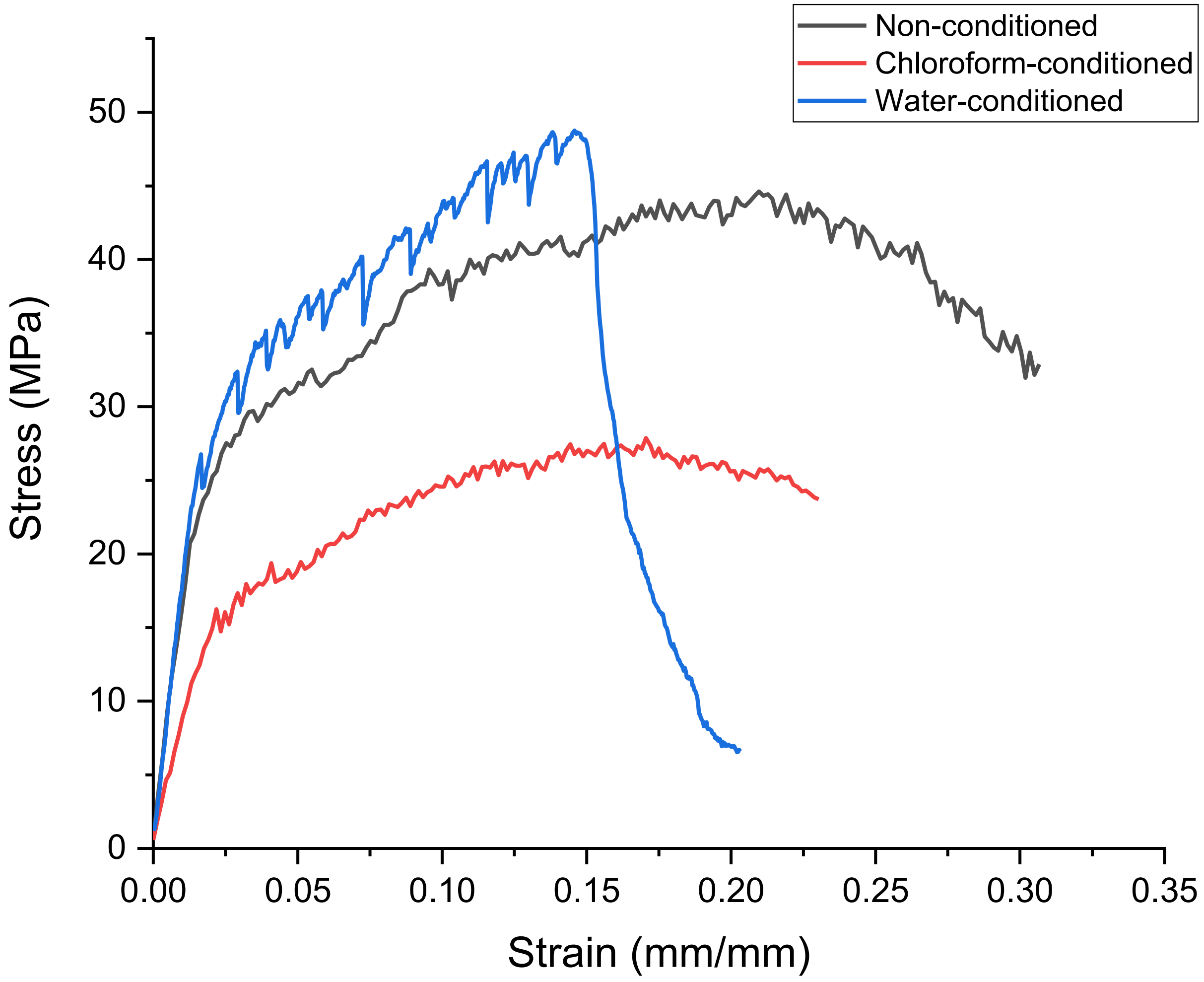


- Crack initiated but no fracture observed because of ductile behavior

- Strong fiber/matrix adhesion caused detrimental failure of water conditioning specimens
- The brittle behavior caused by the leached of monomers and induced hygrothermal aging

- No fracture observed because of ductile behavior
- Chloroform conditioning weakening the interface between the inner and outer layers.
- Delamination was observed .

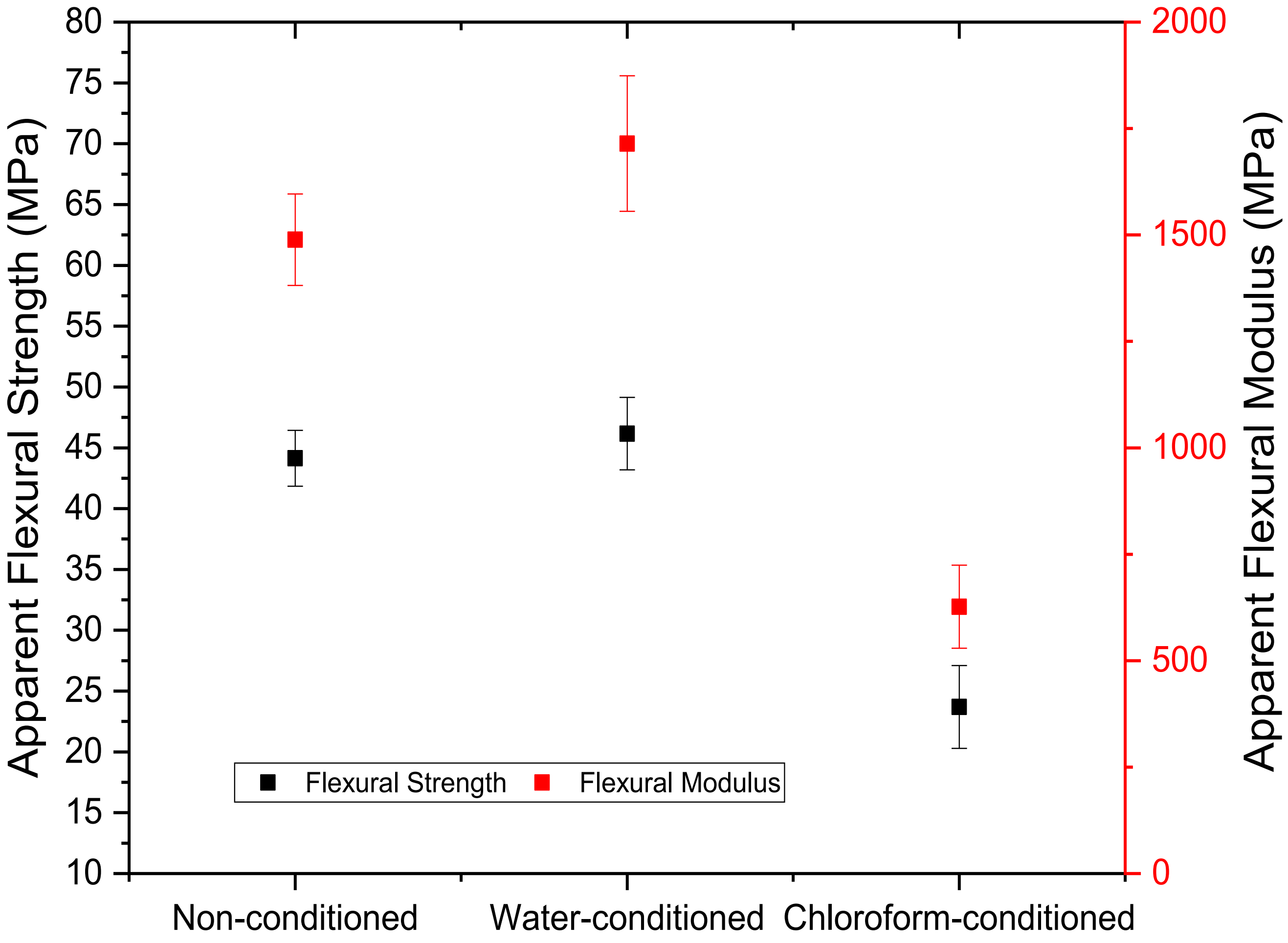
Toughness changes drastically upon conditioning



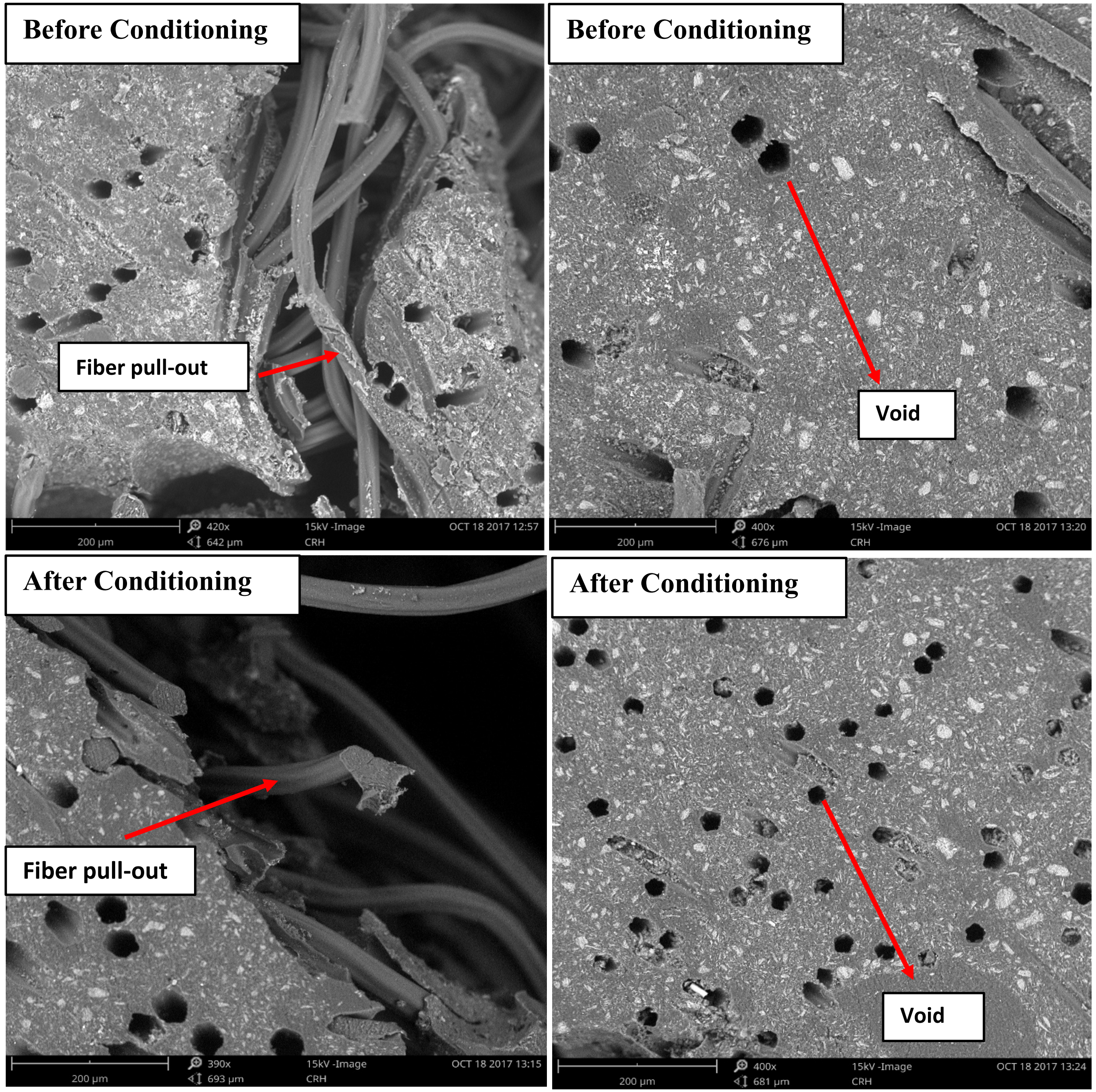
- Non-conditioned - ductile behavior was observed
  - Due to the plasticization from residual styrene and other organic molecules.
- Chloroform - similar ductile behavior was observed
  - Possibly due to plasticization effect of residual chloroform
    - the method needs tweaking
- Water – embrittlement observed.
  - Likely due to residual styrene extraction

CIPP is not “inert” and may change over time

Mechanical properties change due after water and solvent conditioning



- Water leaches out residual organic molecules (styrene) which marginally increase both strength and modulus
  - Residual styrene acts as a plasticizer
- Chloroform decreases strength and modulus due to matrix cracking and delamination
  - Due to solvent swelling
  - Due to plasticization of solvent



	Void Diameter, mm	Fiber Diameter, mm
Average	0.0435	0.043833
Stdev	0.003202	0.003804

Recommendations

- Should test for residual monomer via TGA for VOC (styrene)
  - Will help determine if material is fully cured
  - Standard spec is needed
  - TGA <u>should not</u> be used for non-volatile non-styrene resins.
- Mechanical testing should happen to make sure meets spec
  - Will only detect potential manufacturing defects
- Proper sampling placement should happen
  - Multiple places, outside surface, furthest away from heat source, in wet areas.
- Accelerated Aging standards should be developed, validated, and utilized.
  - May help determine if longevity/aging failure will happen
  - Probably best combined with NDE test of quality/aging.

Evidence-Based Practices for Successful Lining Projects

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January 14, 2019 Washington, DC USA

Session 1178 TRB Annual Meeting

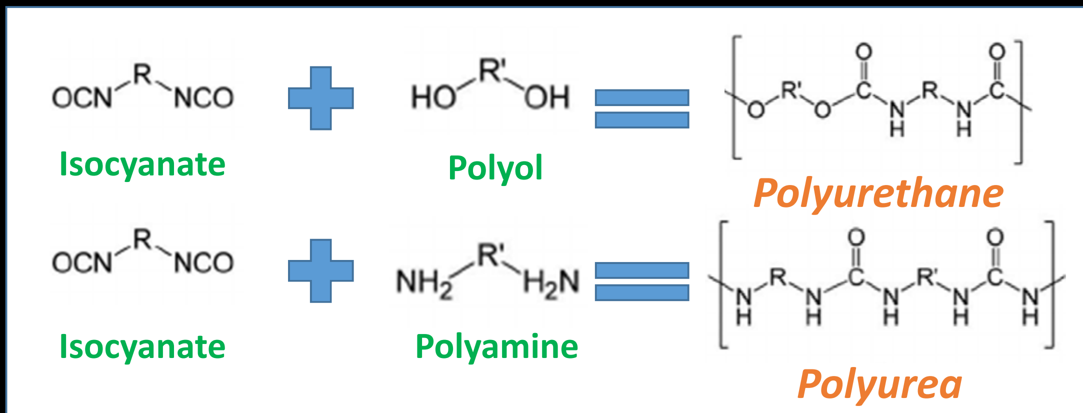
Stormwater culverts and repairs in the U.S.

12 million+ linear feet of culvert in place (FHWA 2005)

1 million+ existing culverts require rehabilitation (FHWA 2010)

Mechanical failures can be catastrophic (traffic disruption, public safety)

Several culvert repair technologies chemically manufacture the product at the culvert site – Inside the Asset



Spray-on and CIPP Lining Practices

- Contractors manufacture (or create) a new product in the field.
- Chemicals are brought onsite, curing is conducted.
- Administrative and engineering controls vary according to our observations (sometimes by necessity – but need to be documented).
  - Ventilation, standing water, proximity to roadway, access to rinse water and sewer
- Construction inspector is needed for these manufacturing sites (trained on what to look for, specification enforcement

VDOT has the most detailed spray-on lining specifications which were based on field and laboratory testing

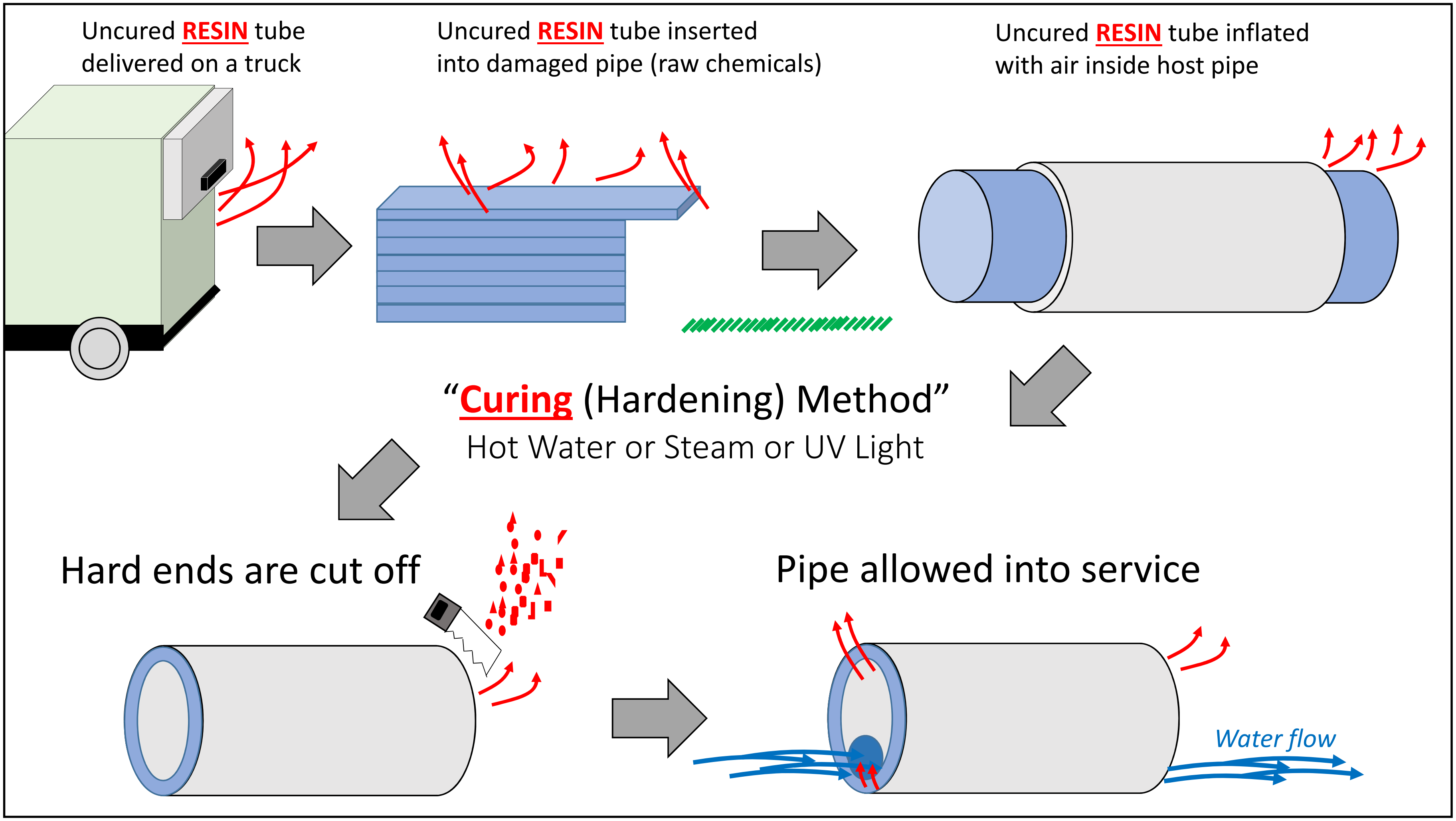
Cement Mortar Coating

- Install temporary curtain at the outlet and inlet to prevent overspray during installation.
- Reinstate flow NO SOONER THAN 24 hours following installation
- Prevent escape of rinse water and capture it, monitor pH. When below pH 9, can be released, otherwise transport for off-site disposal.

Polyurea Coating

- Qualified independent environmental services laboratory or environmental consultant to collect water samples
- Sample within 3 ft of the pipe ends: Before rehabilitation, and within 1 week after the pipe liner has cured
- If water is not available to sample, samples of rinse water shall be used for the analyses
- Analyzed for total methylene diphenyl diisocyanate (MDI), methylenedianiline (MDA), and total cyanide. MDI and MDA in water samples shall not exceed 1,000 mg/L and 39 mg/L, respectively
- Analyze for chemical oxygen demand (COD) and total nitrogen (TN)
- Submit a completed within 4 weeks after completion of rehabilitation
- Contractor’s responsibility to report and take appropriate corrective actions to remediate any water quality alteration resulting from the lining materials in accordance with applicable local, state or federal regulations. The cost for such remediation shall be at the Contractor’s expense.

Additional testing is needed to ascertain chemical emission from spray-on linings


Uncured RESIN tube
delivered on a truck
Uncured RESIN tube inserted
into damaged pipe (raw chemicals)
Uncured RESIN tube inflated
with air inside host pipe
"Curing (Hardening) Method"
Hot Water or Steam or UV Light
Hard ends are cut off
Pipe allowed into service
Water flow

How long does a CIPP last?

“50 year design life”?
“100 year design life”?
Some CIPPs installed for 30 years already

CIPP manufacturing sites are highly transient, single installation being used from a few hours to a few days.

Unlike traditional manufacturing operations, no ‘permanent address’ to visit or inspect

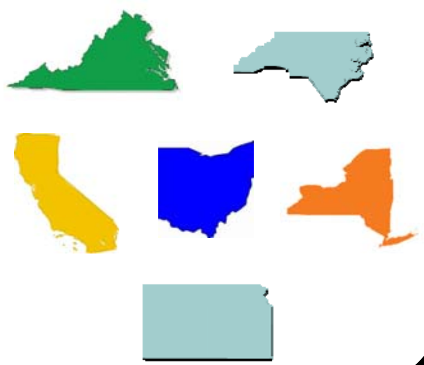
Once complete, workers packup and move on

Contaminant Release from Storm Water Culvert Rehabilitation Technologies: Understanding Implications to the Environment and Long-Term Material Integrity, 2016-Present

Goal: To enable DOT informed decisions with regard to culvert polymer in-situ lining method selection and specification development.

Objectives: (1) The scope of the problem across DOTs; (2) The effectiveness of existing construction specifications at minimizing contaminant release from rehabilitated culverts; and (3) The degree to which the structural integrity and longevity of rehabilitated culverts are compromised by chemical leaching.

Our Partners



1. Critical Review: Spray-on lining chemical release
2. Critical Review: CIPP lining chemical release
3. Feedback from 32 DOTs about in-situ lining practices
4. Thermal-CIPPs: Field- and Bench-scale studies
5. UV-CIPPs: Field- and Bench-scale studies
6. **Recommendations for lining jobs** and future work

There are several factors that have contributed to past chemical contamination incidents

SPECIFICATION did not articulate how to and when contractors should prevent environmental contamination

CONSTRUCTION INSPECTOR did not understand the type and magnitude of chemical emissions or when they can occur

ENGINEERING FIRM did not understand the type, magnitude of chemical emissions, or when they can occur

CONTRACTORS did not understand the type and magnitude of chemical emissions from the technology

CONTRACTORS did not follow the construction specifications

Q: What actions are needed to appropriately reduce the chances that a lining project causes public and environmental impacts?

Worksite Practices

Cutting a UV uncured resin tube exposes raw chemicals to the environment

Use glide sheets to avoid uncured resin tube contact with the ground and water

Workers can spread contamination: Do not contact PPE (boots, gloves, etc.) and then contact other materials

Chemical release potential: Dust released when cutting new CIPP

Less than a pinch of CIPP dust released 16 mg/L styrene into water in the lab in only 24 hours

Plywood prevented the uncured resin tube from contacting standing water

Wastes are a Problem

Chemical release potential: Condensate

Do not permit rinse water to enter the environment

Do not permit discharge to the environment to include curing water, wastewater, rinsewater, condensate, particulates

Chemical release potential: Blisters with bubbling liquid can rupture and leak

Cutting materials created during new CIPP cutting

Do not let liner materials contact the water

Monitoring and Documentation Needed: Evidence of Immediate Impacts

Construction inspector required, it is a plastic manufacturing site

- Needs to know what to look for
- Pictures (required) and video (very helpful)
- Interfacial temperature monitoring upstream, downstream needed

Visible floating debris is outlawed in some states and Clean Water Act

Water testing required and plan if failure is detected

Water samples should not be grabbed by the contractor. They do not have qualifications/training, and have a significant conflict of interest

DOTs should hire 3^{RD} party laboratory to conduct testing

- Upstream, downstream before and after CIPP manufactured
- List of chemicals in our recommendations, not just styrene

A variety of chemicals can be released from a CIPP manufacturing site and have different aquatic toxicity thresholds

Identified at UV-CIPP sites in our study

Compounds	CAS #	Physical and Chemical Properties					Aquatic Toxicity Thresholds, mg/L			
		MW, g/mol	Water Sol, mg/L at 25°C	Vapor Pr, mmHg 25°C	Log K_{ow}	Log K_{oc}	*D. magna*, 48 hr LC_{50}	Algae, 48 hr LC_{50}	Fathead minnow, 48 hr LC_{50}	Rainbow trout, 48 hr LC_{50}
Acetophenone	98-86-2	120.15	6,130	0.397	1.58	1.71	528.7 [23]	-	163 [24]	-
Benzaldehyde	100-52-7	106.13	6,950	1.27	1.48	1.04	50[a] [25]	-	15.8 [26]	12.6 [26]
BADGE	1675-54-3	340.42	0.7	1.1E-07	3.84	3.81	-	-	-	-
BHT	128-37-0	220.36	0.6	5.2E-03	5.10	4.17	1.44[d] [27]	-	-	-
Decane	124-18-5	142.29	0.052	1.43	5.01	3.16	18 [28]	-	-	> 1000[b] [29]
DBP	84-74-2	278.35	11.2	2.0E-05	4.50	3.06	2.99[d] [30]	3.5[d] [31]	1.49 [32]	1.60[b] [30]
1-Dodecanol	112-53-8	186.34	4	8.5E-04	5.13	2.63	0.765[e] [33]	-	1.01[b] [34]	-
Ethylbenzene	100-41-4	106.17	169	9.6	3.15	2.65	2.12 [35]	4.6[e] [36]	-	-
Irgacure® 184	947-19-3	204.27	-	-	2.81	1.92	59.3[d] [37]	14.4[e] [37]	-	-
Maleic anhydride	108-31-6	98.06	3,700	0.25	1.62	1.36	330[d] [38]	> 150[e] [38]		75[b] [38]
Isopropylbenzene	98-82-8	120.20	61.3	4.50	3.66	2.84	0.6 [35]	2.6[e] [36]	-	5.8 [39]
Phenol	108-95-2	94.11	82,800	0.35	1.46	2.27	12 [28]	-	28[b] [40]	5.8 [41]
Phthalic anhydride	85-44-9	148.12	6,000	5.2E-04	1.60	1.00	> 640[d] [42]	60-350[f] [42]	-	-
N-Propylbenzene	103-65-1	120.20	52.2	3.42	3.69	2.91	2.21[c] [43]	1.8[e] [36]	-	-
Styrene	100-42-5	104.15	300	6.40	2.95	2.65	23 [28]	0.56[d] [44]	12 [44]	6.6[b] [45]
Styrene oxide	96-09-3	120.15	3,000	0.30	1.61	2.06	21.6 [46]	32[f] [47]	4.54[b] [46]	-
1-Tetradecanol	112-72-1	214.39	0.191	1.1E-04	6.03	3.15	3.2[d] [48]	-	-	-
1,2,3-TMB	526-73-8	120.20	75.2	1.69	3.66	2.80	-	-	-	-
1,2,4-TMB	95-63-6	120.20	57	2.10	3.63	2.79	3.6 [35]	-	7.72[b] [49]	-
1,3,5-TMB	108-67-8	120.20	48.2	2.48	3.42	2.78	6 [35]	25[d] [31]	-	-
m-Xylene	108-38-3	106.17	161	8.29	3.20	2.57	9.56 [35]	4.9[e] [36]	-	8.4[b] [36]
p-Xylene	106-42-3	106.17	162	8.84	3.15	2.57	8.49 [35]	3.2[b] [36]	-	2.6[b] [36]

Monitoring:

- Evidence of Impact (are remedial measure necessary?)
- Evidence of Good Practices and Compliance

Water Testing:

- Before Setup, During Manufacture?
- After Manufacture

What to Test for? (research study or general)

- Specific Chemicals (What's in the formulation?)
- Surrogate Parameters (COD)

Water Sampling and Testing

Scientific Studies – Defined by research objectives

Monitoring for compliance – (Field documentation: Written w/ Photos)

- Specify containers (glass with or without headspace, liners?)
- Specify sampling methods (distances, locations, ppe, etc.)
- Type of sample (with preservative, with solvent) – i.e., samples for organic analysis, for COD analysis, pH? How many sub-samples?
- Rinse water control sample (Chlorine?)
- Laboratory analyses?

Project Testing: Evidence of CIPP Quality

Report the amount of % weight of volatile material that exists in the CIPP

- Use upstream and downstream sample from the sides. If liner installed when water was present, samples should be collected from inner and outer of those locations as well.

Use Thermogravimetric Analysis (TGA) ASTM E1131

- Take 10–15 mg samples and heat it for 2 hours
- 60 mL/min gas purge flow rate.
- Samples ramped in temperature from 40 °C at 10 °C/min to 160 °C under nitrogen atmosphere
- Hold for 120 min to examine VOC evaporation.
- After 2 hours, report % wt loss

Consider performance based specifications:

- If less than "X" % VOC residual, 100% of contract award price
- If less than "within spec threshold%" VOC residual, 90% of contract award price
- If ">spec threshold%" residual, product fails to meet specifications, must address

Other recommendations coming

CIPPs are created at plastic manufacturing sites. They are not typical construction sites.

Protecting Workers, DOT Employees, Consultants, and the Nearby Public is Important

2018, Nearby employees from 2 government agencies (DOT + 1 other) reported health impacts while observing CIPP manufacture. Injury reporting initiated.

2017, 22-year old CIPP worker died inside a new CIPP, chemical exposure was a contributing factor per OSHA.

2013, 41-year old CIPP worker fell unconscious for 2 minutes inside an uncured resin tube per court documents.

Nearby children and adults have become ill and received medical assistance

What Do We Know? What Can be Done?

- All CIPP practices emit chemicals into the air (steam, hot water, and UV)
- Chemical release occurs during setup, manufacture, and from new CIPPs after contractors leave site
- More chemicals than styrene are emitted into air and have exposure limits
- A non-styrene CIPP emitted styrene into the air
- Steam-CIPP emitted solids, liquids, and gases into the air
- Chemical plumes are sometimes NOT visible, can travel 0.5+ miles
- Environmental, contractor conditions influence the size of the "hot zone"

Setback distances, site physical access controls needed

Dermal and inhalation protections needed

New CIPPs will emit chemicals into the air; Do not enter without testing

Emissions should be captured and disposed. Monitoring should confirm capture, not document how bad the exposure was that could have been prevented.

A Few Conclusions

- All of the problems are significant and can be corrected
- Upgrades needed for spray-on and CIPP lining specifications, 3rd party monitoring, construction inspector duties, and DOT project oversight
- Coming: Evidence-based specs to help avoid contamination and improve CIPP quality control
- Additional monitoring, CIPP product testing, documentation, and oversight needed
- Further tests should be conduct to understand the variety of chemicals used and released
- Help should be requested from:
  - Clean Water Act administrators
  - Worker safety agencies (NIOSH, etc.)
- DOTs need to directly engage in the safety of their employees and the public

DOTs and Contractors should reach out to NIOSH for advice, a "technical assistance" request, and/or –FREE– onsite testing.

Thank You

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A copy of these presentations and associated reports
for this study can be found at our website: www.CIPPSafety.org