Development and Validation of a New Accelerated Test Method to Predict the Service Life of Corrugated HDPE Pipes Manufactured with Post-Consumer Recycled Materials

November 18, 2019

UMD
University of Minnesota Duluth
Driven to Discover

Outline

- Research objectives
- Overview of corrugated HDPE pipe and recycled materials
- Service life considerations of corrugated HDPE pipe containing recycled materials
    - Development of a new test method for pipes containing recycled materials
    - Service life prediction model
- Results of research

Research Objectives

- Evaluate the viability of incorporating post-consumer recycled materials into corrugated HDPE pipes for highway drainage applications
    - Environmental benefits
    - Cost benefits
- Determine the effects of post-consumer recycled materials on the service life and durability of corrugated HDPE pipes
- Develop appropriate specifications and material standards for corrugated HDPE pipes manufactured with recycled materials for highway applications

Research Sponsors

- NCHRP Project 4-32 – “*Performance and Quality Control of Corrugated Pipe Manufactured with Recycled Polyethylene Content*” - *$300K*
- NCHRP Project 4-39 – *“Field Performance of Corrugated HDPE Pipes Manufactured with Recycled Materials” - $650K*
- Southeastern Pennsylvania Transit Authority (SEPTA) – sponsored PhD dissertation work with Villanova University

TRB
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SEPTA

Corrugated HDPE Pipe Overview

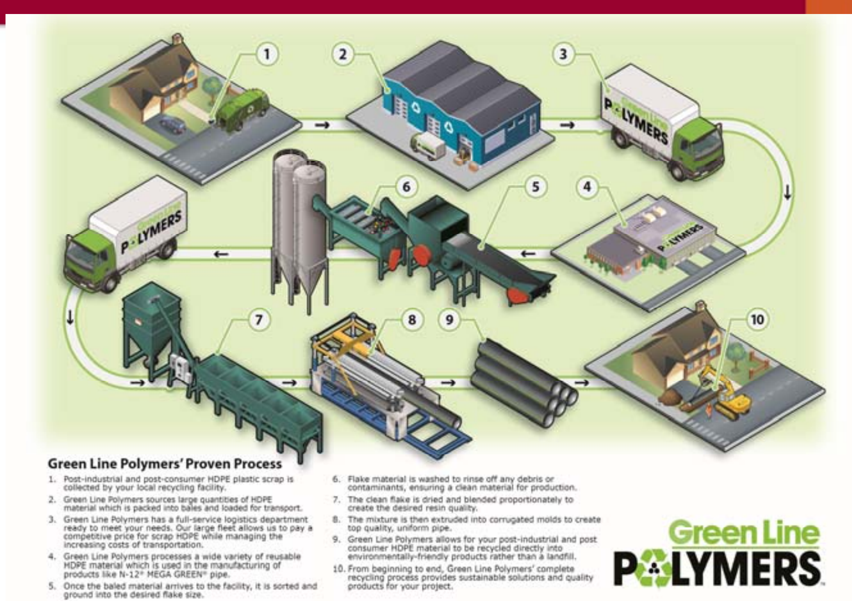
- Used for storm sewers, culverts and land drainage applications
- Highway standards have traditionally required product to be manufactured with 100% virgin materials
- Manufactured in 4 in. to 60 in. diameters and 20-ft lengths
- Attractive over competitive materials due to resistance to corrosion and abrasion and durability

Recycled Materials for Corrugated HDPE Pipe

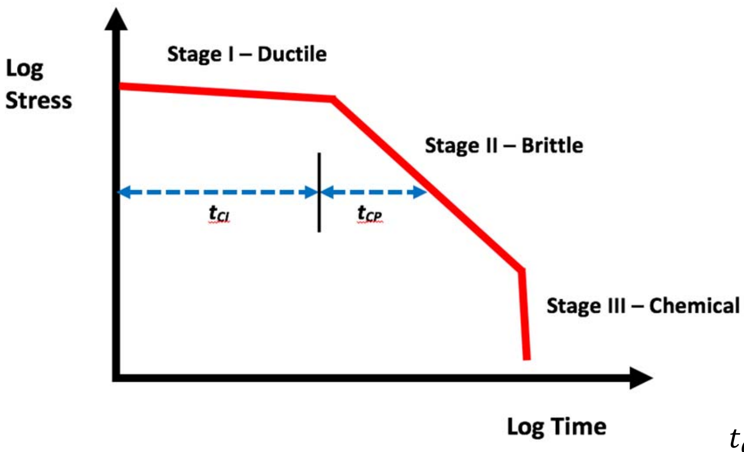
- Post-industrial recycled (PIR) materials (pre-consumer)
  - UL Definition: "Material diverted from the waste stream during a manufacturing process that has never reached the end user."
  - May include reject parts, regrinds, defective parts, etc. from another manufacturer
- In-plant regrind materials
  - Scrap or out-of-spec parts
  - Scrap materials from start-up

Recycled Materials for Corrugated HDPE Pipe

- Post-consumer recycled (PCR) PE materials
  - PE materials from products that have served a previous consumer purpose
  - Flake or reprocessed pellets
  - More readily available than PIR materials and more consistent in performance, though may have lower stress crack resistance
  - Approx. 5.5 billion pounds of these materials in agricultural and land drainage pipes over past 20 years!



Service Life Considerations for HDPE

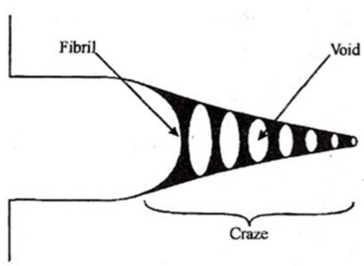


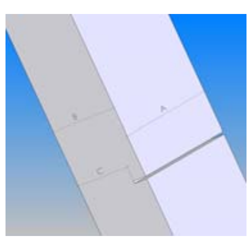
Creep:
$$t_{CCG} = t_{CI} + t_{CP}$$

Fatigue:
$$N_{FCG} = N_{CI} + N_{CP}$$

t_{CI} = time for crack initiation
t_{CP} = time for crack propagation

Slow Crack Growth (SCG) Evaluation





Notched Tests

$$t_{SCG} = t_{CI} + t_{CP}$$

where

t_{SCG} = total time for slow crack growth
t_{CI} = time for crack initiation
t_{CP} = time for crack propagation

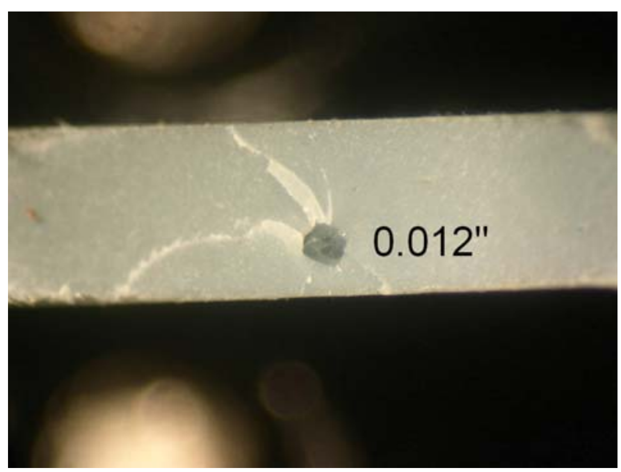
Constant Stress Testing – A New Test Method – UCLS Test

Designation: F3181 – 16

Standard Test Method for The Un-notched, Constant Ligament Stress Crack Test (UCLS) for HDPE Materials Containing Post- Consumer Recycled HDPE[1]

This standard is issued under the fixed designation F3181; the number immediately following the designation indicates the year original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

- Invented to assess the crack initiation phase as well as the crack growth phase
- Conducted in DI water at elevated temperatures



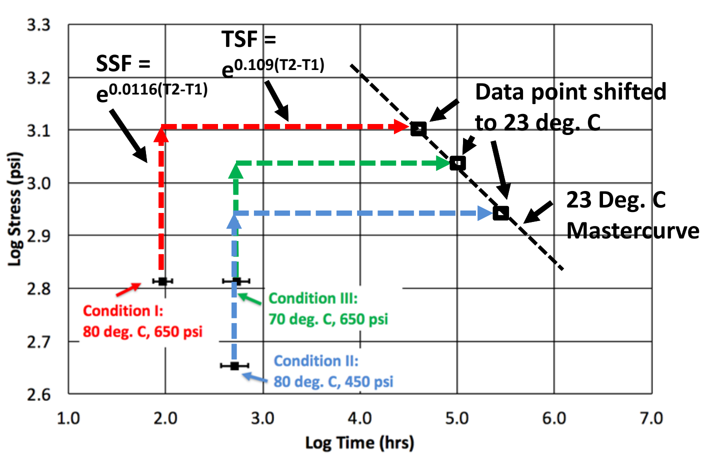
Predicting Service Life Relative to Brittle Cracking with the UCLS Test

- Conduct UCLS test in water at at least 3 different temperature / stress conditions (E.G. 80 deg. C / 650 psi; 80 deg. C / 450 psi; 70 deg. C / 650 psi)
- Use Popelar Shift Method (PSM) or Rate Process Method (RPM) to shift data from test temperature and stress to service temperature and stress:

Popelar Shift Method: *Stress Shift Factor* = $e^{0.0116(T2-T1)}$
Time Shift Factor = $e^{0.109(T2-T1)}$

Rate Process Method: $$\log t = A + \frac{B}{T} + \frac{C \log S}{T}$$

Illustration of Service Life Prediction
Pipe 4 – 49% PCR – UCLS Data shifted to 23 deg. C



- Demonstration of bi-directional shifting using Popelar Shift Factors
- Shift elevated-temperature data to service temperature

Illustration of Service Life Prediction
Pipe 4 – 49% PCR – UCLS Data Shifted to 23 deg. C

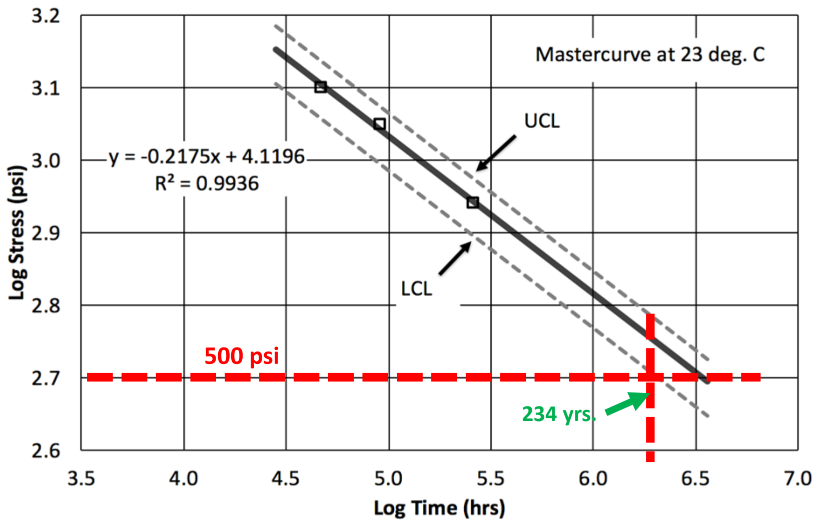
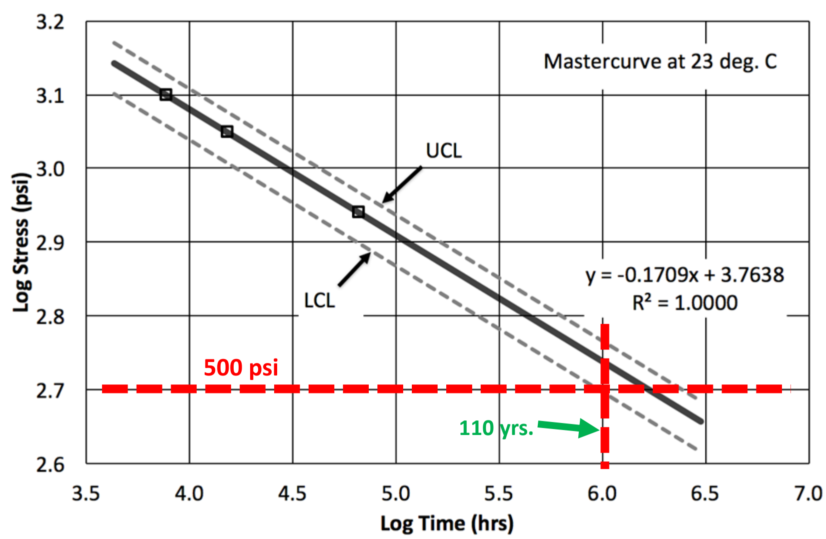


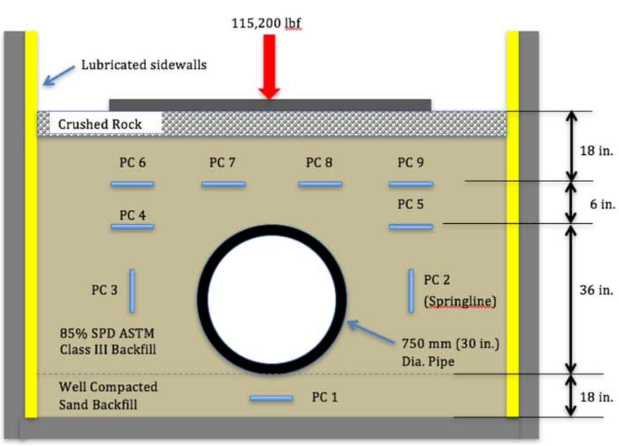
Illustration of Service Life Prediction
Pipe 3 – 98% PCR Pipe – UCLS Data Shifted to 23 deg. C



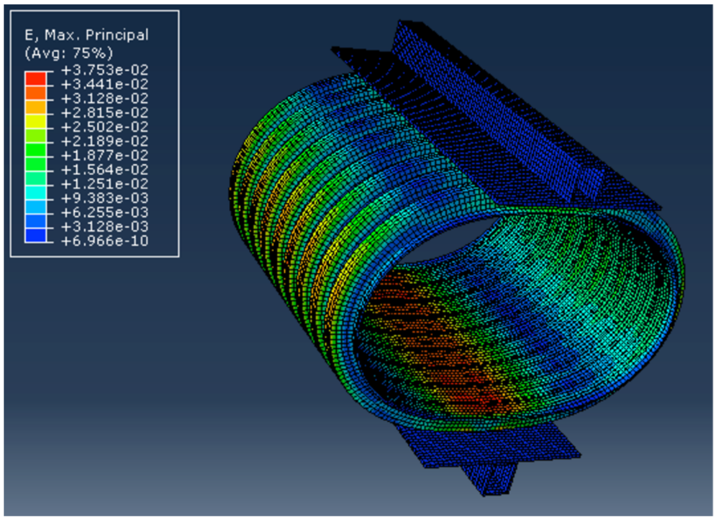
Model Validation

- The next step was to validate the service life prediction model on full-scale pipes in simulated extreme installation conditions
- Required producing pipe with blends of materials that were designed to fail within a year so that the model could be validated in a reasonable timeframe

Simulated Field Test



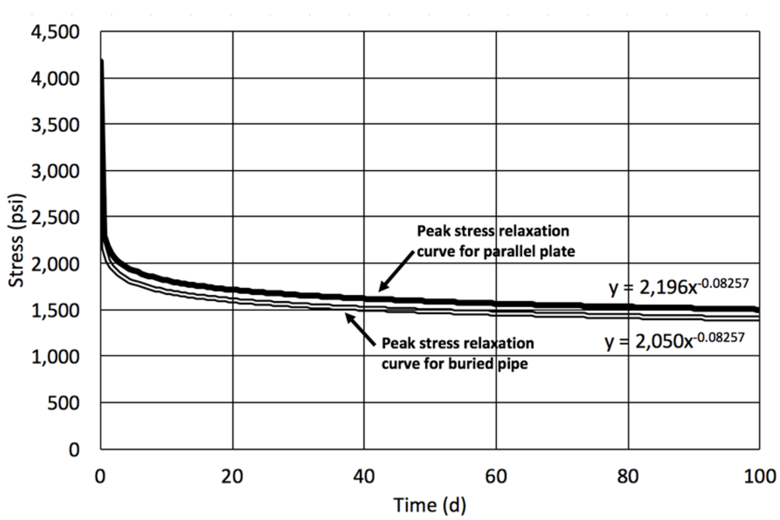
Strain Analysis



Peak local strain at 20% deflection = 3.75%

Peak tensile strain in simulated field test on buried pipes = 3.5%

Equivalent Average Stress Determination



$$\overline{\sigma_{PP}} = \frac{\int_0^{100} 2196x^{-0.083}}{100} = 1637\ psi$$

$$\overline{\sigma_{Buried}} = \frac{\int_0^{100} 2050x^{-0.083}}{100} = 1528\ psi$$

Illustration of Service Life Prediction
Pipe 4 – 49% PCR – UCLS Data Shifted to 23 deg. C

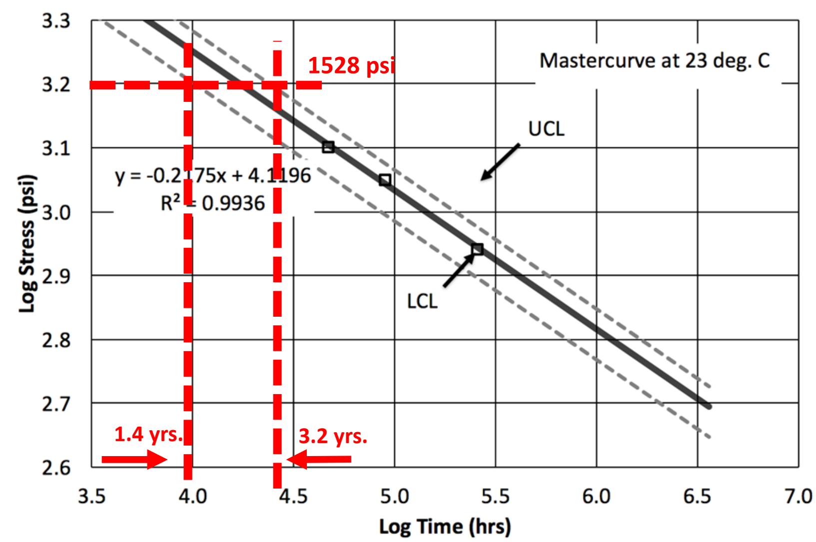
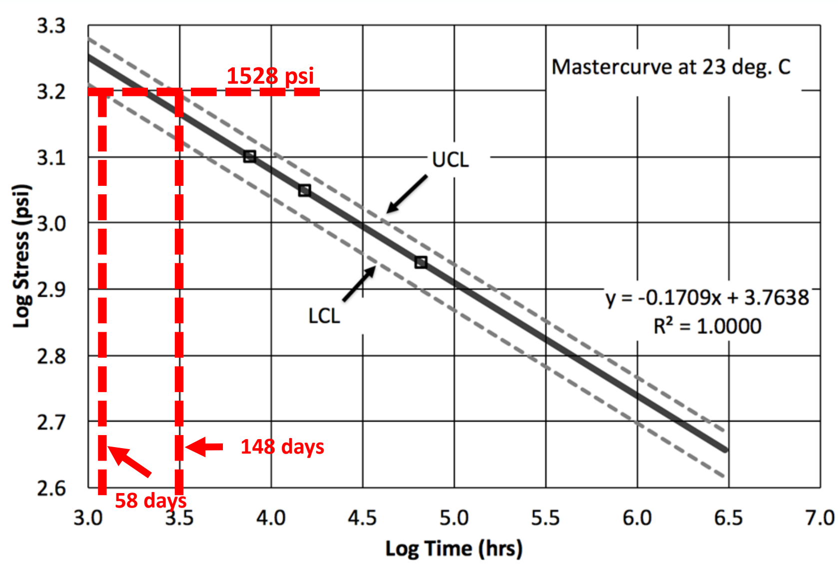


Illustration of Service Life Prediction
Pipe 3 – 98% PCR Pipe – UCLS Data Shifted to 23 deg. C



Full Scale Pipe Validation Testing in Accelerated Loading Conditions

Pipe	Description	PCR	Predicted Time to Cracking	Actual Time to First Cracking
Pipe 1	30 in. M294 pipe	0%	> 2 yrs.	> 1 yr. - No cracks
Pipe 2	30 in. F2648 pipe	49%	> 2 yrs.	> 1 yr. - No cracks
Pipe 3	30 in. Custom pipe	98%	58 – 148 days	101 days
Pipe 4	30 in. F2648 pipe	49%	1.4 – 3.1 yrs.	> 1 yr. - No cracks
Pipe 5	30 in. M294 pipe	0%	> 2 yrs.	> 1 yr. - No cracks
Pipe 6	30 in. Custom pipe	98%	71 – 220 days	185 days
Pipe 7	30 in. Custom pipe	98%	73 – 172 days	185 days
Pipe 8	30 in. F2648 pipe	54%	203 - 578 days	> 306 d - No cracks
Pipe 9	30 in. F2648 pipe	59%	139 – 357 days	300 days

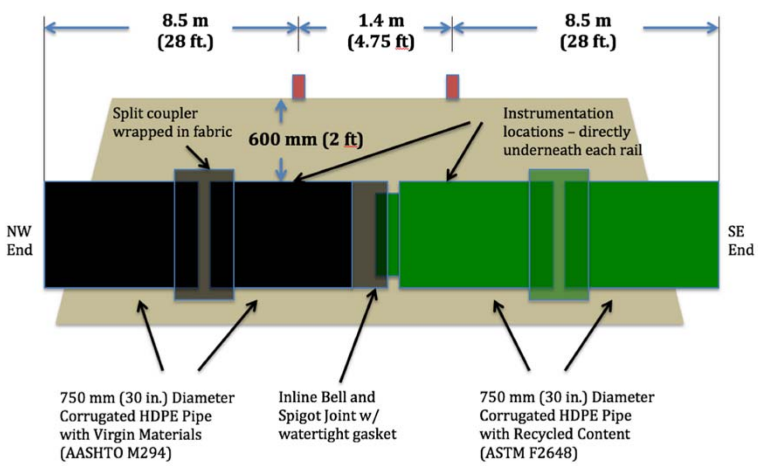
Cracking in Pipe 3 – 98% PCR Pipe



Highlights of Service Life Prediction Method

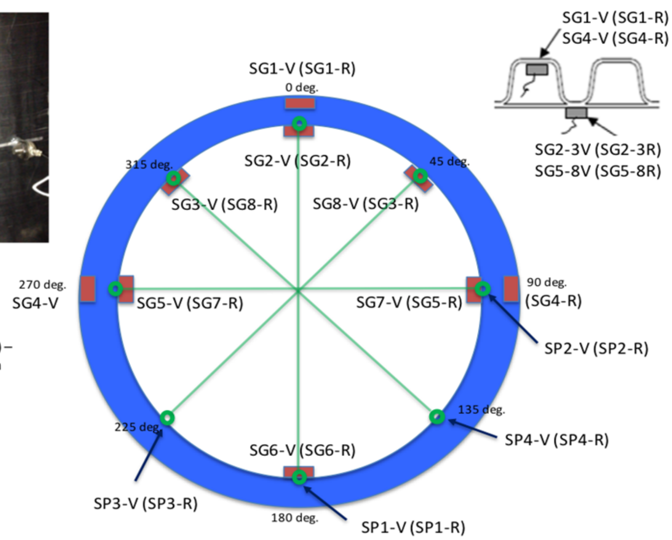
- Every pipe that was predicted to crack developed cracks within the predicted timeframe, both for the parallel plate test and the simulated field test
- None of the pipes that were not predicted to crack developed cracks
- Based on these test results, the service life prediction model based on the UCLS test was validated
- The UCLS test provides the basis for a true performance-based specification for pipes manufactured with recycled materials
- *Note: The validation tests are extreme tests and are not typical of actual installations; Additionally, the pipes were formulated with blends of materials designed to crack within a reasonable timeframe*

3-Year Evaluation under Heavy Rail Loads



- Virgin and PCR 750 mm (30 in.) diameter pipes with bell and spigot watertight joint
- 0.6 m (2.0 ft.) of cover to bottom of tie
- Pipes instrumented with strain gages and extensometers

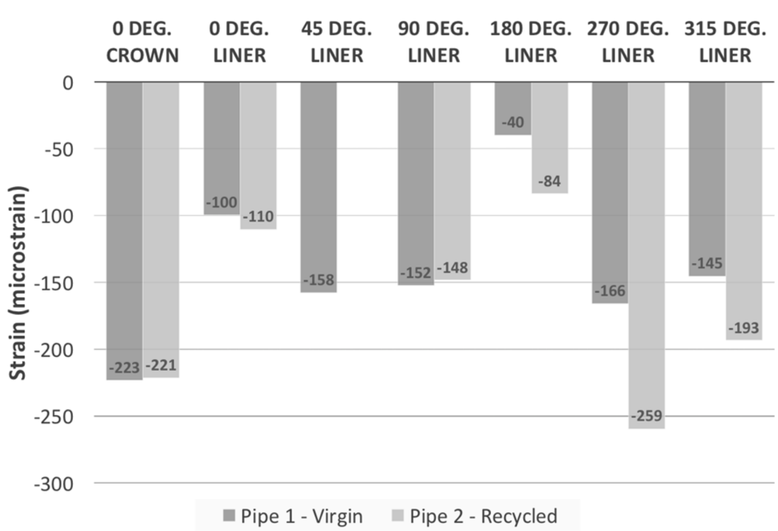
Example strain gage placement for (SG4-R) – drill out access hole in liner to access inner surface of outer wall



3-Year Evaluation under Heavy Rail Loads

3-Year Evaluation under Heavy Rail Loads

Dynamic Wall Strain Comparison



Research Results and Deliverables

- Draft revisions to AASHTO M294 were developed to include the incorporation of corrugated HDPE pipes manufactured with recycled content – includes 33-hr. UCLS requirement
  - Balloted and passed in 2017, published June 2018
- Revisions to AASHTO Bridge Design Specifications to include material properties for pipes manufactured with recycled materials
- A new ASTM test method was developed for the UCLS test
  - Published 2016
- A new AASHTO Standard Recommended Practice was developed for establishing the service life of corrugated HDPE pipes manufactured with recycled content and for determining the minimum UCLS criteria to ensure the desired service life is met
  - Passed AASHTO ballot 48-0; will be published March 2019

Summary of M 294 Changes

Property	Test Method	M 294 V	M 294 R
Cell Classification	ASTM D3350	435400C	435400C
NCLS	ASTM F2136	18 hours liner; 24 hours plaque	18 hours liner; 24 hours plaque
OIT	ASTM D3895	Not required	20 minutes
Elongation at Break	ASTM D638	Not required	150%
UCLS	ASTM F3181	Not required	34 hours*
Markings		"M 294 V" – every 10 feet	"M 294 R"; "Contains Recycled Resins" – every 10 feet

* Ensures 100-year service life at 23 deg. C at a factored wall stress of 500 psi

Standard Recommended Practice for Service Life Determination

Standard Recommended Practice for

Service Life Determination of Corrugated HDPE Pipes Manufactured with Recycled Materials

AASHTO Designation: M xxx-yy[1]
Technical Section: No., Name
Release: Group n (Month yyyy)

AASHTO

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001

- Details procedure for determining the service life of corrugated HDPE pipes manufactured with recycled materials
- Provides equations to determine the minimum UCLS requirements to ensure service life at given conditions
- Balloted in October 2018, passed 48-0
- Will be published March 2019

Determining Minimum UCLS

$$t_T = 10^C / SF_t$$

where

$$C = \left[\frac{\log(SF_\sigma * \sigma_T) - \log(\sigma_{SVC})}{m}\right] + \log(t_{SVC})$$

t_T = time to failure @ test cond., hrs.
m = slope of brittle curve
SF_σ = Stress shift factor
SF_t = Time shift factor

t_{SVC} = service life, hrs.
σ_{SVC} = design stress at service cond., psi
σ_T = stress at UCLS test condition, psi

Adjust for 95% Confidence

$$LCL_{95\%} = t_T = \bar{X}_{95\%} - t_{(n-1)}\left(\frac{COV * \bar{X}_{95\%}}{\sqrt{n}}\right)$$

$$\bar{X}_{95\%} = \frac{t_T}{\left[1 - \left(\frac{t_{(n-1)} * COV}{\sqrt{n}}\right)\right]}$$

X_{95} = Minimum UCLS test requirement
t_T = time to failure @ test cond., hrs.
t_{n-1} = t-statistic for 95% CI = 2.132
COV = Maximum coefficient of variation = 0.5
n = number of test specimens = 5

Summary and Conclusions

- The purpose of these research projects was to evaluate the viability of incorporating post-consumer recycled materials into corrugated HDPE pipes for highway drainage applications
- The research demonstrated that corrugated HDPE pipes manufactured with recycled materials can have a service life exceeding 100 years
- Revisions to AASHTO M 294 were adopted in 2018, and pipes containing recycled materials are currently being installed underneath highways in several states as a result
- A new test method for the UCLS test was published by ASTM
- A new AASHTO standard practice for determining service life of these pipes was balloted in October 2018 and will be published this year

Summary and Conclusions

- There are 3 final reports summarizing the research that led to the recommendations in M 294:
  - NCHRP Report 696, *“Performance of Corrugated Pipe Manufactured with Recycled Polyethylene Content”,* by Rick Thomas and David Cuttino
  - NCHRP Report 870, *“Field Performance of Corrugated HDPE Pipes Manufactured with Recycled Materials”*, by Michael Pluimer, PhD; Joel Sprague, PE
  - PhD Dissertation, *“Evaluation of Corrugated HDPE Pipes Manufactured with Recycled Content in Commuter Rail Applications”,* by Michael Pluimer, PhD

Questions?