The Ohio Department of Transportation
Office of Research & Development
Final Report

Phase 1: Proof of Concept Validation of Methodology to Examine the Responsible Use of Recycle in Corrugated Polyethylene (PE) Drainage Pipe

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Phase 1: Proof of Concept Validation of Methodology to Examine the Responsible Use of Recycle in Corrugated Polyethylene (PE) Drainage Pipe

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1.0 Statement of the Problem

Corrugated High Density Polyethylene (HDPE) pipe has been successfully used in a variety of applications for many years. Recently, there has been interest in the responsible use of recycled materials in corrugated HDPE pipe. Prior to full use of these materials, the potential impact of recycle materials on pipe performance needs to be characterized. This Research Program is to demonstrate Proof of Concept of a methodology for examining the viability of utilizing recycle in corrugated polyethylene (PE) drainage pipe.

2.0 Objective of the Study

The objective of this Research Program was to demonstrate Proof of Concept of a methodology for examining the viability of utilizing recycle in corrugated HDPE drainage pipe. As stress crack resistance is the critical property for determining pipe durability, the proposal focuses on the proof of concept and preliminary development of a methodology to generate accelerated stress crack resistance data enabling projection and validation of in-service performance.

3.0 Test Item Identification and Description

The following samples, as shown in Table 1, were provided by a manufacturer. No further detail of the samples was provided.

Table 1: Sample Description

Jana Sample ID	Description
05-102	18″ Black corrugated pipe, 10′ long **(Pipe Containing Recycle)**
05-545	18″ Black corrugated pipe, 20′ long **(Control Pipe)**

4.0 Background

Corrugated HDPE pipe has been successfully used in a variety of applications for many years. Recently, there has been interest in the responsible use of recycled materials in corrugated HDPE pipe. In 1997, PPI (Plastics Pipe Institute) published a report entitled “A Stress Crack Resistance Method for Evaluation of Polyethylene Materials Intended for Pipe Applications”. In this report the NCTL (Notch Constant Tensile Load) test was introduced as a method of measuring the slow crack growth (SCG) resistance of the PE material used to make PE pipe. It is well recognized that SCG is the long-term failure mode observed in PE pressure pipe failures. PPI reported that the SCG resistance of a PE blend material, when measured by the NCTL test, could either increase or decrease when a recycled material was added based on the NCTL value of the original recycled material. PPI's research work showed that this NCTL test method could be used to characterize the SCG resistance of PE materials, and in particular, PE blends that incorporate recycled materials. Through the efforts of PPI, the NCTL test method was developed as an ASTM test method and is now known as the NCLS (Notch Constant Ligament Stress) test – ASTM F 2136. AASHTO now references this NCLS test method in its corrugated HDPE pipe standard M-294 for evaluation of base PE materials. In January 2003, PPI issued Statement U, "PPI Position Statement on Use of PCR (post consumer recycled) Materials in Polyethylene Pipe". PPI had recognized the desire to use recycled materials in non-pressure pipe applications. The PPI position on recycled materials was to "support work toward defining performance requirements, material properties and test criteria that will result in the responsible use of consumer recycled materials in polyethylene pipe used for non-pressure applications".

Recognizing the need for research in the responsible use of recycled materials in corrugated HDPE pipe, in August 2003, the AASHTO Subcommittee on Materials approved their Research Needs Statement, "Performance and Quality Control of Corrugated Polyethylene Pipe Manufactured from Recycled Polyethylene Material". AASHTO's defined research need on the recycled material blend and the finished pipe was as follows:

> *This research statement outlines the overall objective to determine the maximum allowable polyolefin and other contaminant levels without adversely affecting long-term service life. Additionally this research is needed to validate a post-production test performed on finished pipe for recycled materials. This post-production test should provide assurance of long-term stress crack resistance at levels currently required for pipe made from virgin product, which is currently specified by AASHTO M294. The research must determine if a recycled blend can meet the current resin property requirements specified in the AASHTO Materials Specifications as defined in ASTM D3350.*

A research program was structured to be in harmony with the PPI position on responsible use of recycled materials and to meet the requests of the AASHTO Needs Statement. This report examines the current status of part of that research development program, a new pipe ring test to evaluate SCG resistance. A new pipe ring test method was developed and examined as a potential methodology to determine the SCG resistance of corrugated HDPE pipe. As Finite Element Analysis (FEA) had indicated in past research, the high stress point in the geometry of a corrugated HDPE pipe is at the notch formed between the crown and the liner. The pipe ring test method was designed to introduce a load at this notch stress point in a pipe corrugation. This load is applied to a section of pipe by pressurizing the area between the HDPE pipe's corrugated external wall and the bonded smooth internal wall. By use of FEA, the internal pressure was correlated with the stress at the notch area within the pipe corrugation. By knowing this stress it is possible to apply the well-known Rate Process Method (RPM), which is a mathematical model based on multiple time-temperature-pressure data sets. Through accelerated testing at elevated temperatures and modeling the resulting data, this model allows for projections of SCG resistance at end-use temperatures. Application of this methodology to corrugated pipe made with both virgin materials and with recycle content can then enable a comparison of the effect of recycle materials on SCG resistance.

The advantages of this pipe ring test method are:

- Testing is conducted on the final extruded product
- The sample is more representative of the end-use product as the circumference of the pipe is tested rather than just a small test bar
- This method is applicable to any size corrugated pipe
- The failure modes are similar to testing solid wall pipe – ductile failures at high pressure and brittle (SCG) failures at low pressure
- The test results capture both the period of time for the crack initiation and crack propagation normally seen in SCG failures in finished product
- Extensive modeling techniques for pressure piping, such as the Rate Process Method, appear to be applicable to estimating service life of corrugated HDPE pipe once correlations with stresses in field applications are developed
- The test method can determine the effect of recycled materials on the slow crack growth resistance of HDPE corrugated pipe by comparing to similar pipe made from virgin resin
- The test method may be useful as a post-production quality control test as failures are attainable within a short time frame
- The test method could also be used to determine the effects of secondary loads such as bending and deflection

5.0 Pipe Ring Test Method Evaluation

The test method developed introduces a load at the high stress area between the inner and outer pipe walls by means of an internal pressure. A ring of the pipe corrugation is cut out of the pipe. The vent hole (if present) is removed. Both ends of the pipe ring are capped and sealed, as shown in Figure 1, and the corrugation is subjected to an internal pressure. Pressure testing of the pipe ring is conducted in general accordance with ASTM D1598-02. Testing is conducted at multiple temperature and pressure conditions and the applicability of the Rate Process Method in modeling the resulting data is examined.

Testing was conducted on pipe ring segments from an 18″ control HDPE corrugated pipe with no recycled materials. The pipe was standard commercial production corrugated HDPE pipe meeting the requirements of AASHTO M-294. The NCLS value for the resin blend used to make this pipe was reported by the pipe manufacturer to be 69 hours. The detailed test conditions and test results are provided in Appendix A. Testing was also conducted on a second 18″ HDPE corrugated pipe that was made on the same extrusion machine but contained 50% recycled materials in the resin blend. The NCLS value for the resin blend used to make this pipe was reported to be 93 hours. The detailed test conditions and test results are provided in Appendix A. Visual, optical and scanning electron microscopy (SEM) examination was conducted on laboratory generated pipe ring test failures for comparison to corrugated HDPE pipe exhumed from service. SEM was conducted by an approved subcontract laboratory under the direction of Jana Laboratories. Finite element analysis of the stresses developed in the pipe ring test was conducted by Dr. Ian Moore at Queen’s University.

Testing to ASTM D1598-02 is covered by Jana Laboratories Inc.’s ISO 17025 scope of accreditation (I.A.S. TL-256).

Figure 1: Pipe Ring Test Specimen

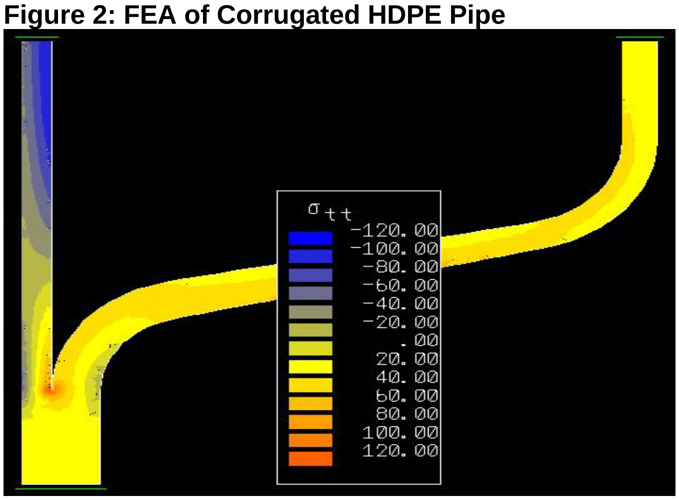
6.0 Finite Element Analysis (FEA)

Professor Ian Moore conducted a finite element analysis of corrugated HDPE pipe and summarized his findings in his paper, “Three-dimensional Response of Deeply Buried Profiled Polyethylene Pipe”. He found a high stress area in the notch between the pipe liner and the crown. This is the location where the two co-extruded walls of the pipe come together and would be expected to be an area with a high stress riser.

In this research project, FEA of the profile geometry of the corrugated HDPE pipe that would be tested in the research program was also conducted to determine the area of highest stress. A correlation between the internal pressure that would be applied during the test and the stress observed by FEA in the corrugated pipe was also developed. The results showed that the internal applied pressure generated tensile bending stresses at the notch tip between the liner and crown of the profile. These stresses are from approximately 100 to 120 times the applied pressure directly at the liner-corrugation connection. The results are shown in Figure 2. This pressure to stress ratio may be dependent on the specific geometry of the pipe and, therefore, the FEA analysis would be product specific. Based on these results it is possible to estimate the corresponding stress at the tip of the notch when an internal pressure is applied. Every one psig of internal pressure corresponds to a stress of 120 psi at the tip of the notch. If the internal pressure is 10 psig, then the corresponding stress is 1,200 psi.

The FEA model, however, does not reliably predict the failure of field samples. For buried pipes, the maximum stresses enforced by loading conditions are developed on the inner surface of the liner elements where they connect to the corrugation valley, whereas for the laboratory test samples the stresses develop on the soil-side of the liner elements at that connection.

Figure 2: FEA of Corrugated HDPE Pipe

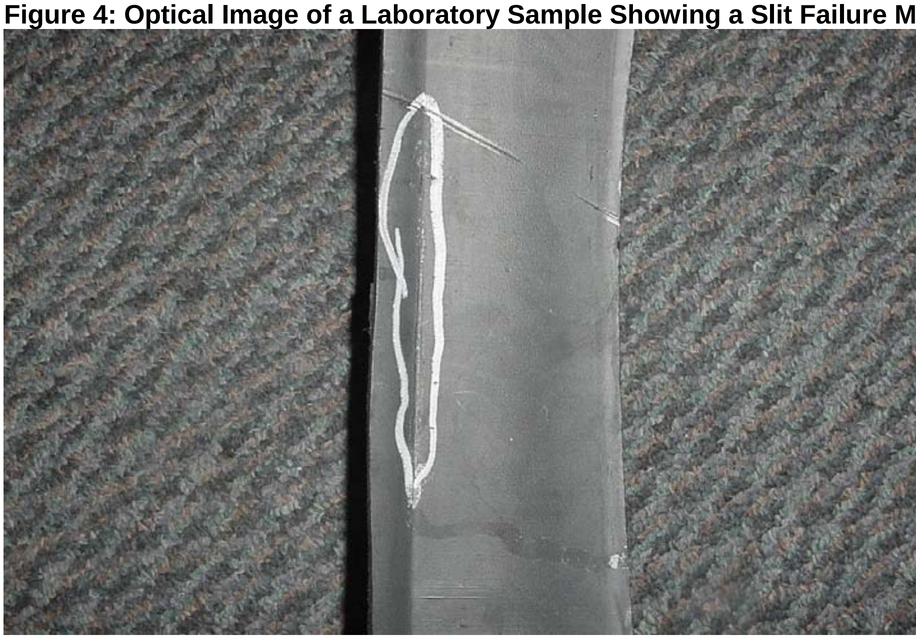


7.0 Analysis of Failure Mechanisms

In developing a laboratory test method to project the performance of recycled materials in corrugated HDPE pipe, it is necessary to ensure that the failure mode in the laboratory method is the same as field observations, regardless of the resin. For laboratory testing it is observed that if the load (internal pressure) is high then a ductile failure occurs in the liner wall. This is the same failure mode observed in solid wall PE pipe when a high internal pressure is introduced inside the pipe. When a lower internal pressure is applied, the failure mode found was a crack that formed at the high stress area between the crown and the liner, also known as the notch tip, and then continued to grow slowly through the liner wall, as shown in Figures 3 and 4.

Figure 3: Optical Image of a Laboratory Sample Showing Cross-section with Failure Point

Figure 4: Optical Image of a Laboratory Sample Showing a Slit Failure Mode



Scanning Electron Microscopy (SEM) photos were taken across this inner liner where the crack propagated and are shown in Figure 5. These SEM photos show the microfibril structure typical of the SCG failure mode and indicate that SCG was indeed the failure mode in this corrugated HDPE pipe ring failure. For the pipe ring laboratory failure, the crack is observed to initiate at the stress concentration area between the crown and the liner. The crack then propagates through the liner wall and around the circumference of the pipe. The failure mechanism is observed to be SCG. Figure 6 shows the SEM analysis of SCG observed under field service conditions. The general failure location and SCG mechanism as observed for the laboratory specimen are observed. The SCG mechanism for the pipe ring test method appears, therefore, to be consistent with the SCG mechanism observed in corrugated HDPE pipe exhumed from service. The implications of duplicating the SCG failure mode in the pipe ring laboratory test method are significant suggesting that the testing methodology can be used with proper modeling approaches to project SCG resistance in corrugated HDPE pipe. Additional SEM photographs are provided in Appendix B.

Figure 5: SEM Images of the Fracture Surface for a Laboratory Generated Failure (Specimen 05-102-11)

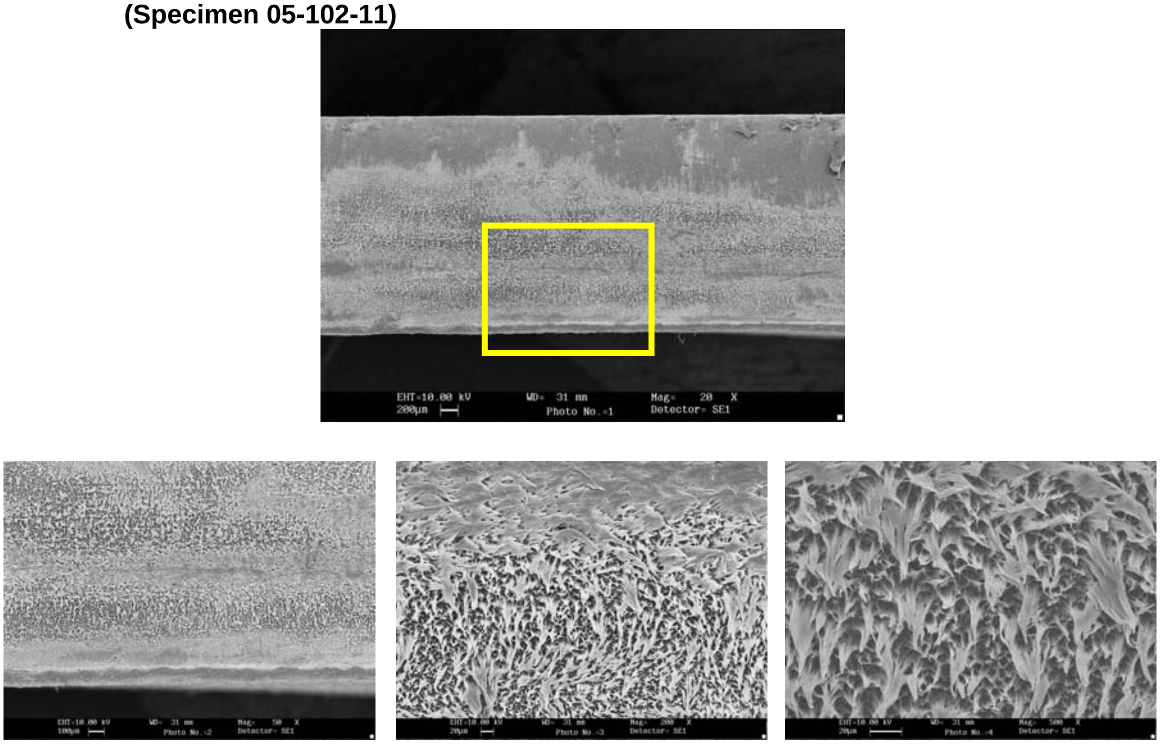
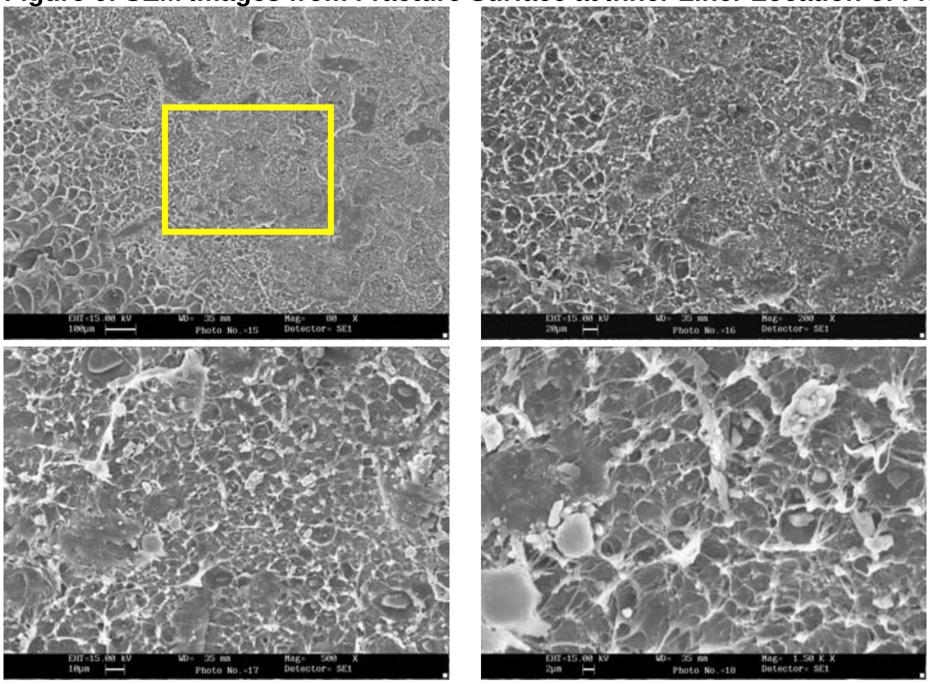


Figure 6: SEM Images from Fracture Surface at Inner Liner Location of Field Pipe



8.0 Rate Process Method (RPM) Analysis

In his paper, "Correlating Aldyl A and Century PE Pipe Rate Process Method Projections with Actual Field Performance", Dr. Palermo demonstrated how RPM is used and compares RPM projections with actual field failures for solid wall gas pipe. There was a very good correlation because both the RPM laboratory failures and the field failures had the same SCG (brittle) failure mode. It is well known that this SCG failure mode follows the principle of Arrhenius for long-term projections (i.e., there is a linear relationship between the logarithm of time and reciprocal temperature).

It would seem reasonable that conducting the same RPM experiment on pipe with recycled materials would enable determination of the effect of the recycled materials on long-term performance. The fit of the Rate Process Model to the pipe ring laboratory test data was examined.

8.1 <u>RPM Data of Pipe with Recycled Material (Sample 05-102)</u>

Table 2 summarizes the test results. Detailed test results are provided in Appendix A.

Table 2: Summary of Test Results (Sample 05-102)

Temperature	Test Pressure (psig)	Stress* (psi)	Failure Time (hr)	Failure Mode
194 °F (90 °C)	2	240	539.75	Slit
	6	720	14.50	Slit
			14.50	Slit
			59.50	Slit
	8	960	14.50	Slit
			24.25	Slit
			24.25	Slit
176 °F (80 °C)	4	480	109.00	Slit
			85.00	Slit
			61.00	Slit
	6	720	36.00	Slit
			36.00	Slit
			25.75	Slit
	8	960	36.00	Slit
			12.50	Slit
			12.50	Slit
	10	1,200	5.65	Slit
	12	1,440	4.53	Slit
158 °F (70 °C)	6	720	179.75	Slit
			124.75	Slit
			83.75	Slit
	8	960	122.50	Slit
			84.50	Slit
			84.50	Slit
			84.25	Slit
140 °F (60 °C)	6	720	420.75	Slit
			204.25	Slit
			204.25	Slit

* Estimated stress at liner-junction interface based on FEA

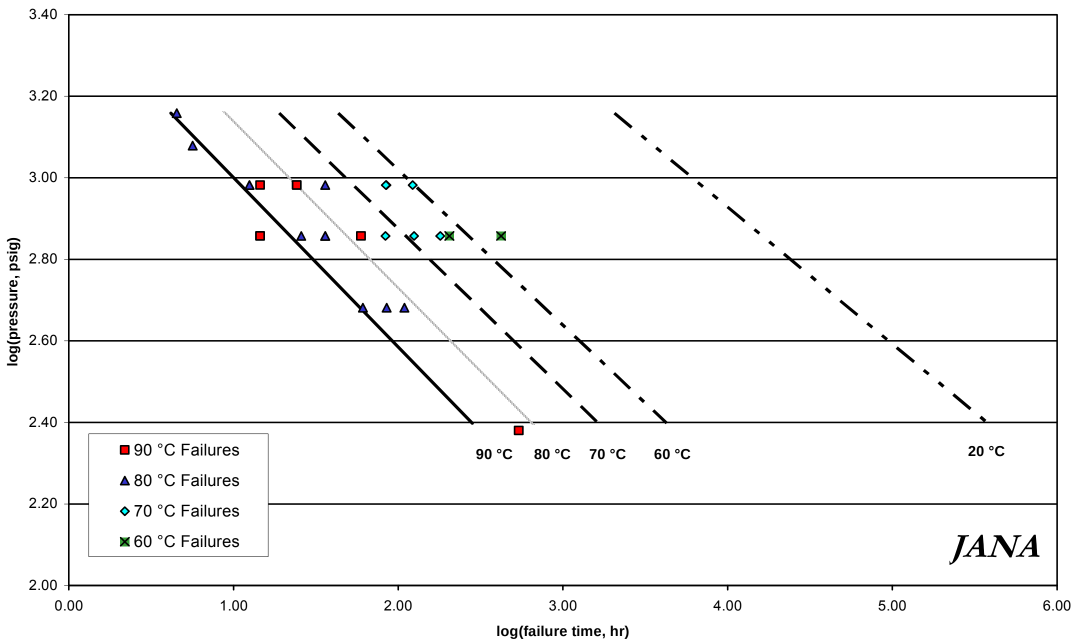
The failure data for the pipe containing recycle generated using the pipe ring test method was fitted to the three-coefficient Rate Process Method model. The regression equation is:

Log (Failure Time) = – 10.6574 + 6,856/T – 874.0/T*Log (Hoop Stress)
Where Failure Time is hours, T is kelvin, Hoop Stress is psi.

R^2 (regression coefficient): 0.770
Number of Data Points: 28
Number of Failure Points: 28

The elevated temperature data and RPM projections are shown graphically in Figure 7. The lines are the slope of the brittle or SCG curve as predicted by the regression. The 68 °F (20 °C) regression line is the projected SCG performance curve of the corrugated HDPE pipe with recycle at a typical end-use temperature. From this 68 °F (20 °C) regression line, one can determine the projected average failure time for this same SCG failure mode at a selected stress and at an average ground temperature of 68 °F (20 °C). Since the three RPM coefficients are known, any desired average ground temperature may be selected for the projection.

Figure 7: RPM Analysis of HDPE Corrugated Pipe Containing Recycle



8.2 RPM Data of Control Pipe (Sample 05-545)

Table 3 summarizes the test results. Detailed test results are provided in Appendix A.

The failure data for the control pipe generated using the pipe ring test method, was fitted to the three-coefficient Rate Process Method model. The regression equation is:

Log (Failure Time) = – 11.5773 + 6,142/T – 463.7/T*Log (Hoop Stress)
Where Failure Time is hours, T is kelvin, Hoop Stress is psi.

R^2 (regression coefficient):	0.777
Number of Data Points:	20
Number of Failure Points:	20

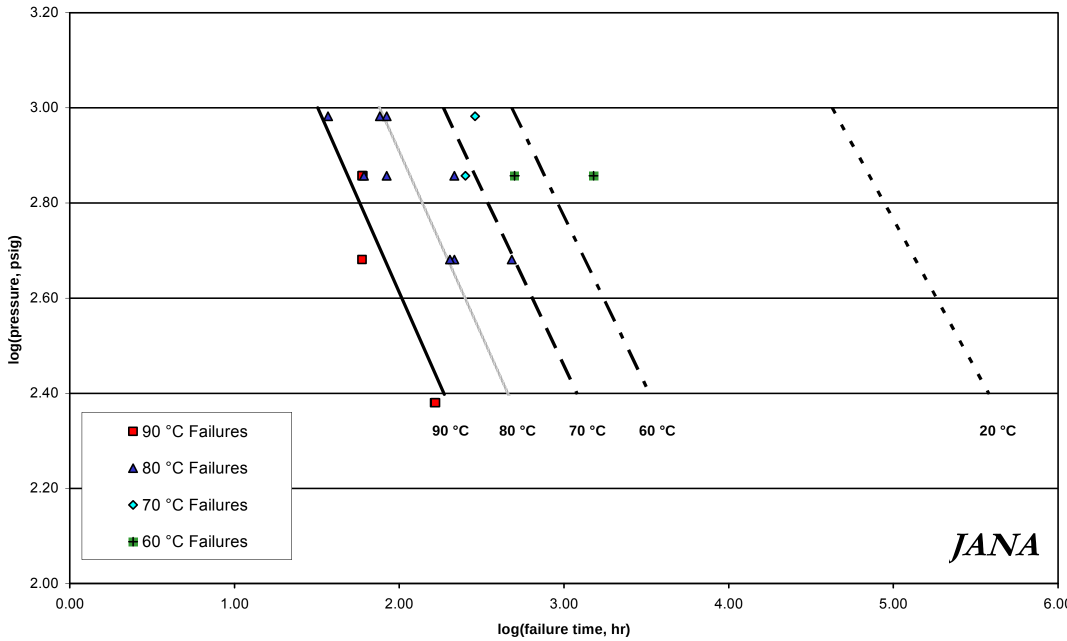
Table 3: Summary of Test Results (Sample 05-545)

Temperature (°F)	Test Pressure (psig)	Stress* (psi)	Failure Time (hr)	Failure Mode
194 °F (90 °C)	2	240	1,175.50†	Slit
			164.25	Slit
			166.00	Slit
	4	480	59.50	Slit
	6	720	60.25	Slit
			59.75	Slit
			59.75	Slit
176 °F (80 °C)	4	480	482.42	Slit
			216.00	Slit
			203.25	Slit
	6	720	84.00	Slit
			61.00	Slit
			216.00	Slit
	8	960	84.00	Slit
			76.25	Slit
			37.00	Slit
158 °F (70 °C)	6	720	252.25	Slit
			84.25†	Slit
	8	960	289.00	Slit
	9	1,080	996.50†	Slit
140 °F (60 °C)	6	720	501.75	Slit
			501.75	Slit
			1,511.00	Slit

* Estimated stress at liner-junction interface based on FEA
† Statistical outlier. Not used in the RPM analysis

The elevated temperature data and RPM projection at 68 °F (20 °C) are shown graphically in Figure 8. These regression lines are based on the three coefficients of the RPM model for the control pipe. All failure modes are SCG that initiated in the notch between the liner and crown and propagated through the liner wall as was the case with the pipe containing recycle. This 68 °F (20 °C) regression line is the projected SCG performance curve of the control HDPE corrugated pipe at typical end-use temperature. From this 68 °F (20 °C) regression line, one can determine the projected average failure time for this same SCG failure mode at the selected stress and at an average ground temperature of 68 °F (20 °C). Again, since the three RPM coefficients are known, any desired average ground temperature may be selected for the projection.

Figure 8: RPM Analysis of Control HDPE Corrugated Pipe

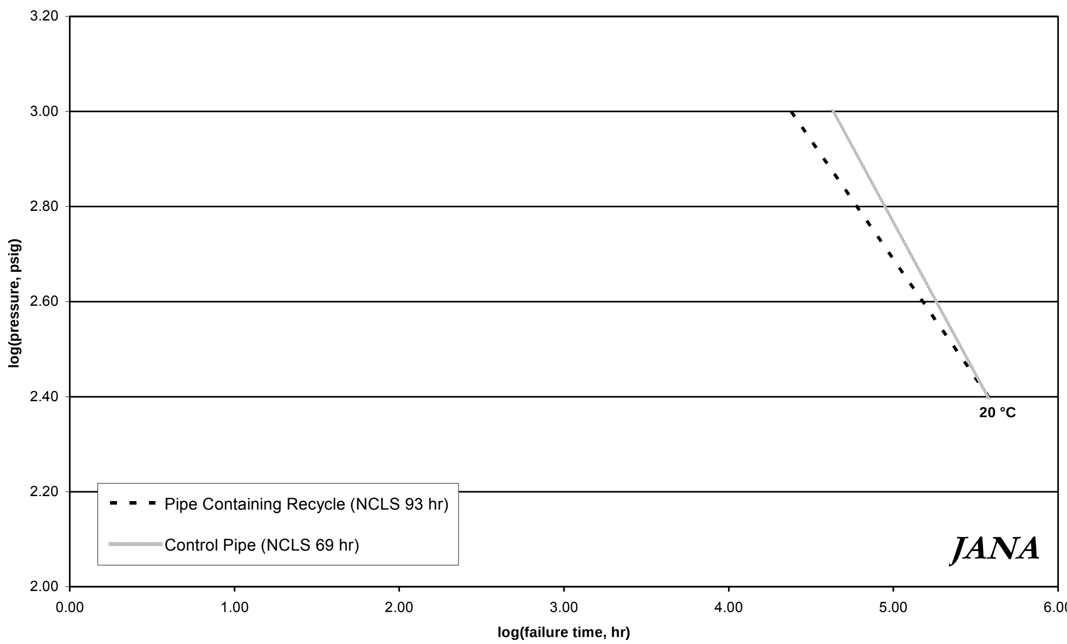


Using the regression equations for the two materials, it may be possible to determine the effect of recycled materials on HDPE corrugated pipe. This has been done in Figure 9 with a comparison of the 68 °F (20 °C) regression lines of the control pipe and pipe containing recycle. This plot shows that both lines are virtually overlapping and given the error inherent in the extrapolations the differences are not likely to be significant. There is significant scatter within both data sets (R^2 = 0.8) and the level of scatter is higher than typically seen for solid wall pipe in similar analyses. This scatter is likely attributable to limitations in the test methodology and inherent variability between test specimens. Refinement of the methodology, and in particular pressure control, to reduce variability is recommended.

The known NCLS values at 122 °F (50 °C) for the resins used in the pipes tested showed an approximately 30% higher NCLS value for the pipe with recycle compared to the control. This difference is likely somewhat significant, however, the NCLS test has within laboratory repeatability of about 20% (ASTM F2136-05). As discussed above, the RPM projections at 68 °F (20 °C) in this project have shown no significant differences between the two pipe products so a correlation between the NCLS and the RPM projections can not be performed. However, a correlation between the two may not be technically correct. It is well known in solid wall pipe testing that the crack initiation period can be a very significant portion of the time to failure in SCG type failures. The period of crack initiation is not evaluated in the NCLS test, as the sample is pre-notched.

Therefore, the RPM methodology applied in this project would be able to evaluate the performance of materials and the susceptibility to crack initiation of the finished product.

Figure 9: RPM Projection Comparison



Based on these preliminary data developed, it appears that the Rate Process Method model provides a reasonable fit to the SCG failure data observed in the pipe ring test methodology. Therefore, this test methodology provides a possible means of determining the effect of recycled materials on SCG performance of corrugated HDPE pipe. Additional testing would be required to refine the extrapolations and further assess the suitability of this approach to modeling SCG failures in corrugated HDPE pipe and to provide a correlation between RPM projections and NCLS values.

9. Conclusions

The pipe ring test method appears to be a viable method to access the effect of recycled materials on the slow crack growth resistance of corrugated HDPE pipe, with respect to virgin resins. The SCG mechanism observed in the laboratory pipe ring test method is the same SCG mechanism observed in corrugated HDPE pipe under field service conditions. FEA indicates the high stress area is at the notch formed between the crown and the liner, and this is the failure location for the pipe ring specimen. FEA also provides a correlation between the internal pressure in the pipe ring specimen and the stress at the notch tip. The advantages of the pipe ring test method are:

- Testing is conducted on the final extruded product
- The sample is more representative of the end-use product as the circumference of the pipe is tested rather than just a small test bar
- This method is applicable to any size corrugated pipe
- The failure modes are similar to testing solid wall pipe – ductile failures at high pressure and brittle (SCG) failures at low pressure
- The test results capture both the period of time for the crack initiation and crack propagation normally seen in SCG failures in finished product
- Extensive modeling techniques for pressure piping, such as the Rate Process Method, appear to be applicable to estimating service life of corrugated HDPE pipe once correlations with stresses in field applications are developed
- The test method can determine the effect of recycled materials on the slow crack growth resistance of HDPE corrugated pipe by comparing to similar pipe made from virgin resin
- The test method may be useful as a post-production quality control test as failures are attainable within a short time frame
- The test method could also be used to determine the effects of secondary loads such as bending and deflection

10. Recommendations

Additional development of the pipe ring test method appears warranted based on the preliminary assessment detailed in this report. This development should include:

- Testing of additional pipe sizes, constructions and materials to confirm broad applicability of the method
- Refining the test method to better define parameters that are key in improving reproducibility to generate better predictions
- Refining the test method and equipment utilized to decrease the scatter in the data
- Analysis of additional field samples and installation parameters to determine the conditions that lead to failure
- FEA to correlate field stresses with the stresses in the pipe ring test method to enable performance projections at end-use conditions

11. Implementation Potential

The test method is at a developmental stage, however, it may potentially be used as a post-production quality control test as failures are attainable within a short time frame.

It may have applicability in defining the installation design parameter for different materials and pipe designs. However, further work is required to validate the methodology and develop the relationship between applied test conditions and field installation conditions.

12. Acknowledgments

The investigators would like to thank the Ohio Department of Transportation, Jana Laboratories, Crumpler Plastics, Hancor/ADS, Prinsco and Soleno for co-funding this project.

Appendix A

Test Details

Data Set No. 1: Sample 05-102 at 194 °F – Complete

1. Temperature of test: 194 ± 3.6 °F (90 ± 2 °C)

2. Conditioning time at the test temperature: A minimum of 1 hour

3. Type of end caps: Free end

4. Sample length between end caps: A minimum of 12″

5. Time-to-Failure/Pressure Data:

Specimen ID	Test Pressure (psig)	Total Hours	Status
05-102-06	2	539.75	Slit on Weld Line
05-102-30	6	59.50	Slit on Weld Line
05-102-22	6	14.50	Slit on Weld Line
05-102-23	6	14.50	Slit on Weld Line
05-102-29	8	24.25	Slit on Weld Line
05-102-28	8	24.25	Slit on Weld Line
05-102-24	8	14.50	Slit on Weld Line

6. The test environment inside the specimen – water.
   The test environment outside the specimen – water.

7. No unusual behavior observed during the testing.

8. Dates of test: March 20, 2006 to May 11, 2006

9. Test Supervisor: Tony Kosari

Data Set No. 2: Sample 05-102 at 176 °F – Complete

1. Temperature of test: 176 ± 3.6 °F (80 ± 2 °C)

2. Conditioning time at the test temperature: A minimum of 1 hour

3. Type of end caps: Free end

4. Sample length between end caps: A minimum of 12″

5. Time-to-Failure/Pressure Data:

Specimen ID	Test Pressure (psig)	Total Hours	Status
05-102-14	4	109.00	Slit on Weld Line
05-102-11	4	85.00	Slit on Weld Line
05-102-08	4	61.00	Slit on Weld Line
05-102-27	6	36.00	Slit on Weld Line
05-102-26	6	36.00	Slit on Weld Line
05-102-07	6	25.75	Slit on Weld Line
05-102-25	8	36.00	Slit on Weld Line
05-102-18	8	12.50	Slit on Weld Line
05-102-17	8	12.50	Slit on Weld Line
05-102-02	10	5.65	Slit on Weld Line
05-102-03	12	4.53	Slit on Weld Line

6. The test environment inside the specimen – water.
   The test environment outside the specimen – water.

7. No unusual behavior observed during the testing.

8. Dates of test: November 8, 2005 to April 28, 2006

9. Test Supervisor: Tony Kosari

Data Set No. 3: Sample 05-102 at 158 °F – Complete

1. Temperature of test: 158 ± 3.6 °F (70 ± 2 °C)

2. Conditioning time at the test temperature: A minimum of 1 hour

3. Type of end caps: Free end

4. Sample length between end caps: A minimum of 12″

5. Time-to-Failure/Pressure Data:

Specimen ID	Test Pressure (psig)	Total Hours	Status
05-102-04	6	179.75	Slit on Weld Line
05-102-19	6	124.75	Slit on Weld Line
05-102-15	6	83.75	Slit on Weld Line
05-102-16	8	122.50	Slit on Weld Line
05-102-21	8	84.50	Slit on Weld Line
05-102-20	8	84.50	Slit on Weld Line
05-102-13	8	84.25	Slit on Weld Line

6. The test environment inside the specimen – water.
   The test environment outside the specimen – water.

7. No unusual behavior observed during the testing.

8. Dates of test: March 16, 2006 to April 28, 2006

9. Test Supervisor: Tony Kosari

Data Set No. 4: Sample 05-545 at 194 °F – Complete

1. Temperature of test: 194 ± 3.6 °F (90 ± 2 °C)

2. Conditioning time at the test temperature: A minimum of 1 hour

3. Type of end caps: Free end

4. Sample length between end caps: A minimum of 12″

5. Time-to-Failure/Pressure Data:

Specimen ID	Test Pressure (psig)	Total Hours	Status
05-545-06	2	1175.50	Slit on Weld Line
05-545-19	2	166.00	Slit on Weld Line
05-545-05	2	164.25	Slit on Weld Line
05-545-20	4	59.50	Slit on Weld Line
05-545-26	6	60.25	Slit on Weld Line
05-545-37	6	59.75	Slit on Weld Line
05-545-36	6	59.75	Slit on Weld Line

6. The test environment inside the specimen – water.
   The test environment outside the specimen – water.

7. No unusual behavior observed during the testing.

8. Dates of test: March 16, 2006 to June 23, 2006

9. Test Supervisor: Tony Kosari

Data Set No. 5: Sample 05-545 at 176 °F – Complete

1. Temperature of test: 176 ± 3.6 °F (80 ± 2 °C)

2. Conditioning time at the test temperature: A minimum of 1 hour

3. Type of end caps: Free end

4. Sample length between end caps: A minimum of 12″

5. Time-to-Failure/Pressure Data:

Specimen ID	Test Pressure (psig)	Total Hours	Status
05-545-07	4	482.42	Slit on Weld Line
05-545-22	4	216.00	Slit on Weld Line
05-545-21	4	203.25	Slit on Weld Line
05-545-18	6	216.00	Slit on Weld Line
05-545-16	6	84.00	Slit on Weld Line
05-545-08	6	61.00	Slit on Weld Line
05-545-14	8	84.00	Slit on Weld Line
05-545-15	8	76.25	Slit on Weld Line
05-545-09	8	37.00	Slit on Weld Line

6. The test environment inside the specimen – water.
   The test environment outside the specimen – water.

7. No unusual behavior observed during the testing.

8. Dates of test: March 23, 2006 to May 17, 2006

9. Test Supervisor: Tony Kosari

Data Set No. 6: Sample 05-545 at 158 °F – Complete

1. Temperature of test: 158 ± 3.6 °F (70 ± 2 °C)

2. Conditioning time at the test temperature: A minimum of 1 hour

3. Type of end caps: Free end

4. Sample length between end caps: A minimum of 12″

5. Time-to-Failure/Pressure Data:

Specimen ID	Test Pressure (psig)	Total Hours	Status
05-545-02	6	252.25	Slit on Weld Line
05-545-03	6	84.25	Slit on Weld Line
05-545-01	8	289.00	Slit on Weld Line
05-545-13	9	996.50	Slit on Weld Line
05-545-12	9	84.50	Slit on Weld Line

6. The test environment inside the specimen – water.
   The test environment outside the specimen – water.

7. No unusual behavior observed during the testing.

8. Dates of test: March 16, 2006 to June 1, 2006

9. Test Supervisor: Tony Kosari

Data Set No. 7: Sample 05-102 at 140 °F – Complete

1. Temperature of test: 140 ± 3.6 °F (60 ± 2 °C)

2. Conditioning time at the test temperature: A minimum of 1 hour

3. Type of end caps: Free end

4. Sample length between end caps: A minimum of 12″

5. Time-to-Failure/Pressure Data:

Specimen ID	Test Pressure (psig)	Total Hours	Status
05-102-34	6	420.75	Slit on Weld Line
05-102-33	6	204.25	Slit on Weld Line
05-102-32	6	204.25	Slit on Weld Line

6. The test environment inside the specimen – water.
   The test environment outside the specimen – water.

7. No unusual behavior observed during the testing.

8. Dates of test: May 15, 2006 to June 12, 2006

9. Test Supervisor: Tony Kosari

Data Set No. 8: Sample 05-545 at 140 °F – Complete

1. Temperature of test: 140 ± 3.6 °F (60 ± 2 °C)

2. Conditioning time at the test temperature: A minimum of 1 hour

3. Type of end caps: Free end

4. Sample length between end caps: A minimum of 12″

5. Time-to-Failure/Pressure Data:

Specimen ID	Test Pressure (psig)	Total Hours	Status
05-545-27	6	1511.00	Non-Failure
05-545-24	6	501.75	Slit on Weld Line
05-545-23	6	501.75	Slit on Weld Line

6. The test environment inside the specimen – water.
   The test environment outside the specimen – water.

7. No unusual behavior observed during the testing.

8. Dates of test: May 15, 2006 to July 28, 2006

9. Test Supervisor: Tony Kosari