“NEW TEST METHOD TO DETERMINE EFFECT OF RECYCLED MATERIALS ON CORRUGATED HDPE PIPE PERFORMANCE AS PROJECTED BY THE RATE PROCESS METHOD”

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ABSTRACT

The corrugated HDPE pipe industry is considering the responsible use of recycled materials in their pipe production and also in their pipe standards. One of the key requirements for successful use of recycled materials is ensuring performance of the resulting HDPE corrugated pipe. As slow crack growth (SCG) has been identified as a potential key criterion in long-term field performance for HDPE corrugated pipe, research was undertaken to develop a test method for corrugated HDPE pipe samples that results in laboratory SCG failures that test the highest stress riser in the pipe wall geometry. The test method developed utilizes pipe ring segments that are internally pressurized and tested at elevated temperatures, and result in an SCG failure in the liner wall, which is the highest stress area as measured by finite element analysis (FEA). By applying the mathematical modeling techniques of the Rate Process Method (RPM) on laboratory SCG data obtained on pipe ring samples at multiple temperatures and multiple pressures, it is possible to project the difference in SCG resistance between virgin and recycled materials under service conditions. Once the RPM performance of control HDPE corrugated pipe made with virgin resins is determined, it is then possible to determine the effect of recycled materials by conducting a similar RPM experiment on the same pipe produced with recycled materials. This paper will explain the pipe ring test method, compare SCG failure modes of laboratory data with pipe samples exhumed from field service, describe use of RPM methodology on the laboratory SCG data, and detail the proposed next phase in the development of the methodology.

I. BACKGROUND

Corrugated HDPE (high density polyethylene) 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, “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 D 3350.*

Our research program was structured to be in harmony with this PPI position on responsible use of recycled materials and to meet the requests of the AASHTO Needs Statement. This paper examines the current status of part of that research program to develop a new test method 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 applied to multiple time-temperature-pressure data points. 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 for corrugated HDPE pipe are:

- Testing is conducted on the final extruded product
- The circumference of the pipe is tested rather than just a small test bar; therefore, the sample is more representative of the end-use product
- This method is applicable to any size corrugated pipe
- The failures modes are similar to testing solid wall pipe – ductile failures at high pressure and brittle (SCG) failures at low pressure
- 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 life 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
- The test method could also be used to determine the effects of secondary loads, such as bending and deflection.

II. PIPE RING TEST METHOD EVALUATION SUMMARY

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 D 1598. Testing is conducted at multiple temperature and pressure conditions and the applicability of the Rate Process Method in modeling the resulting data is examined.

Figure 1: Pipe Ring Test Specimen

Finite element analysis of the stresses developed in the pipe ring test was conducted by Dr. Ian Moore, Queen's University (Section III). 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 field service (Section IV). Testing was conducted on pipe ring segments from an 18” control HDPE corrugated pipe with no recycled materials (control pipe). 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 to be 50 hours. The detailed test conditions and test results are provided in Table I (Section VI). Testing was also conducted on a second 18” HDPE corrugated pipe that was made on the same extrusion machine but contained 40% recycled materials in the resin blend. The NCLS value for the resin blend used to make this pipe was reported to be 100 hours. The detailed test conditions and test results are provided in Table II (Section VII).

III. 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 HDPE material walls of the pipe come together and would be expected to be an area with a high stress riser.

In this research project, finite element analysis (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 pipe ring test and the stress observed by FEA in the corrugated pipe was also developed. The results again showed that the circumferential stresses resulting from the internal pressure applied by the test create local bending in the liner and corrugated elements of the profile to produce hoop (circumferential) tensions. These stresses are from 100 to 120 times the applied pressure directly at the liner-corrugation connection.

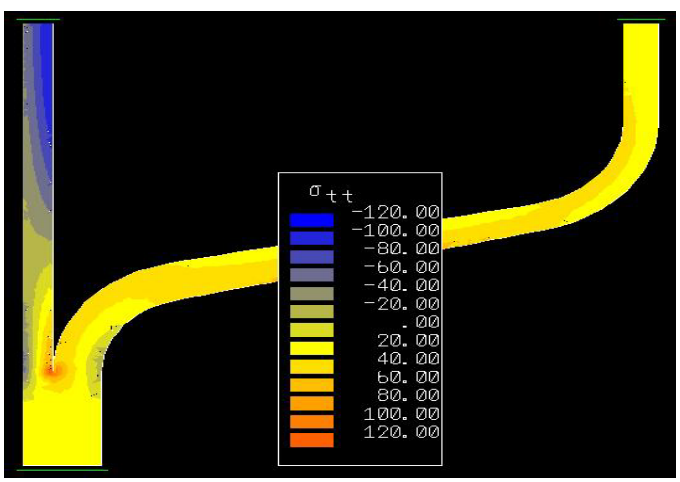

Figure 2: FEA of Corrugated HDPE Pipe

The results are shown in Figure 2. 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 1 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 1200 psi. An analysis to determine the equivalent stresses on the liner under field service conditions is on-going.

IV. SEM 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 used. 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.

Scanning Electron Microscopy (SEM) photos were taken across this inner liner where the crack propagated and are shown in Figure 3. 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 laboratory 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 4 shows the SEM analysis of SCG observed under field service conditions. The same general failure location and SCG mechanism as observed for the laboratory specimen are observed in this field specimen. 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 field service. The implications of duplicating the SCG failure mode in the pipe ring laboratory test method are significant suggesting that this testing methodology can be used, with proper modeling approaches, to project SCG resistance of corrugated HDPE pipe, and thus determine the effect of recycled materials on corrugated HDPE pipe.

V. 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.

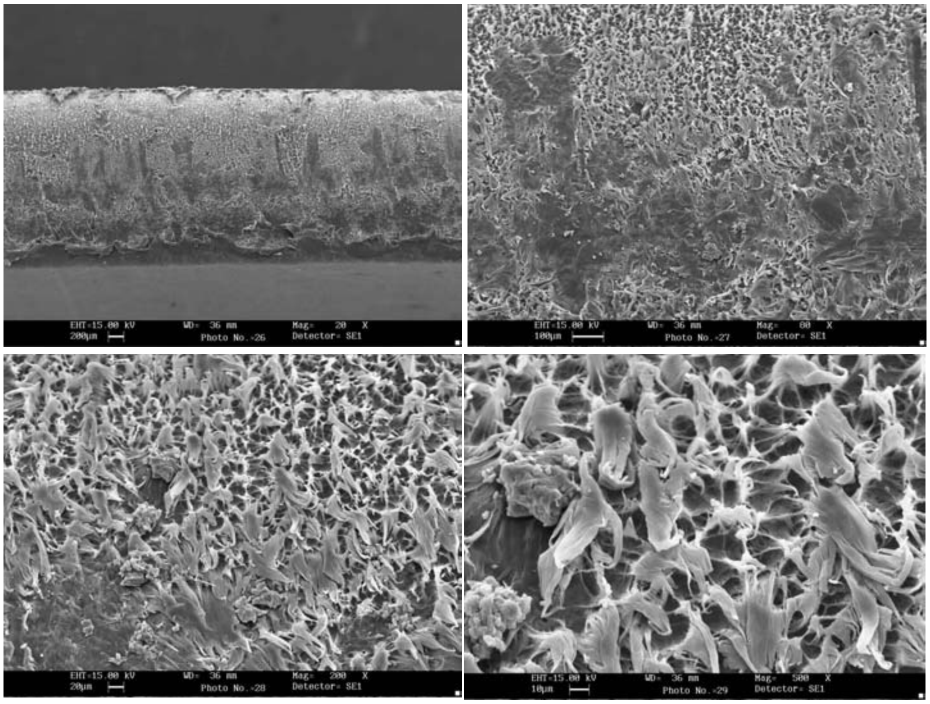

Figure 3: SEM Images of the Fracture Surface for a Laboratory Generated Failure

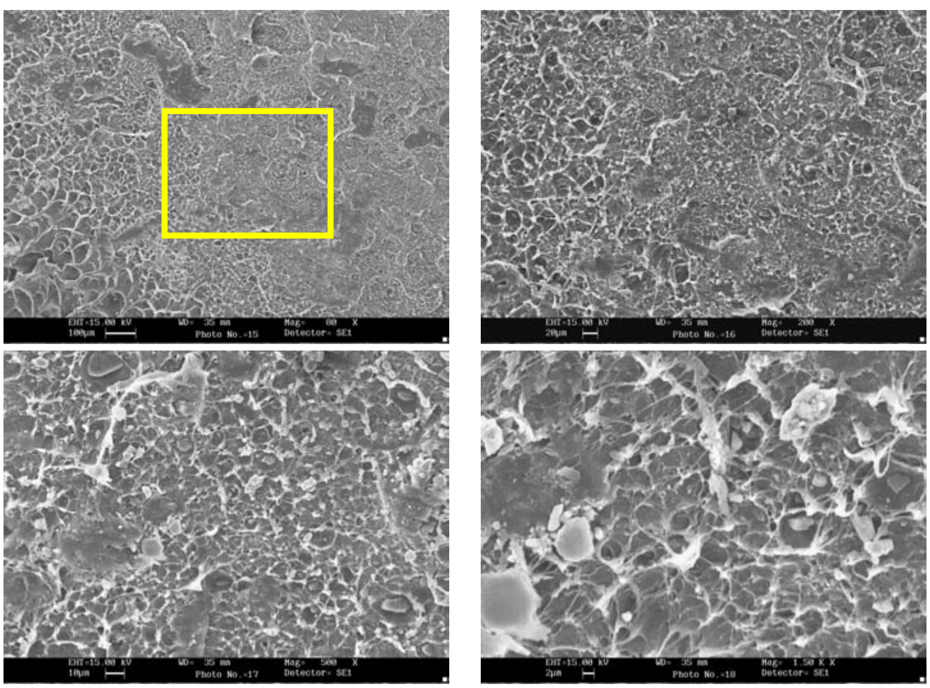

Figure 4: SEM Images from Fracture Surface at Inner Liner Location on Field Pipe

VI. RPM DATA FOR CONTROL PIPE

Table I
RPM Data for 18" Control Corrugated HDPE Pipe

Temperature (°C)	**Pressure** (psig)	**Stress*** (psi)	**Failure Time** (hours)	**Failure Mode**
80	4	480	109	slit
			85	slit
			61	slit
	6	720	36	slit
			36	slit
			26	slit
	8	960	36	slit
			13	slit
			12	slit
	10	1200	6	slit
70	6	720	180	slit
			125	slit
			84	slit
	8	960	122	slit
			85	slit
			84	slit
60	6	720	204	slit
			>200	on test

*estimated stress at liner-junction interface based on FEA

The failure data for the control pipe (Table I), generated using the pipe ring test method, were fitted to the three-coefficient Rate Process Method model. The coefficients and statistics were:

$$\text{Log time} = -22.546 + 10858/T - 829.12*(\text{Log } P)/T.$$

Based on the 17 data points for the control pipe, the correlation coefficient of 0.93 indicates good fit between the data and the RPM mathematical model. For confidence in RPM projections beyond the data, the lack-of-fit probability should be at least 0.05. The “lack of fit” F was 1.5206, and the probability associated with F was 0.26, which indicates a good fit to the RPM model.

The preliminary elevated temperature data and RPM projection at 20°C are shown graphically in Figure 5. The regression lines at 80°C and 70°C are based on the three coefficients of the RPM model. In this case recall that all failure modes are a slow crack that initiated in the notch between the liner and crown and propagated through the liner wall. These regression lines are the slope of the brittle or SCG curve. The 20°C regression line is also based on the same three RPM coefficients, and represents the projected performance of this control corrugated HDPE pipe lot for the same failure mode – SCG through the liner wall. From this 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 20°C. Since the three RPM coefficients are known, any other desired average ground temperature may also be selected for this projection.

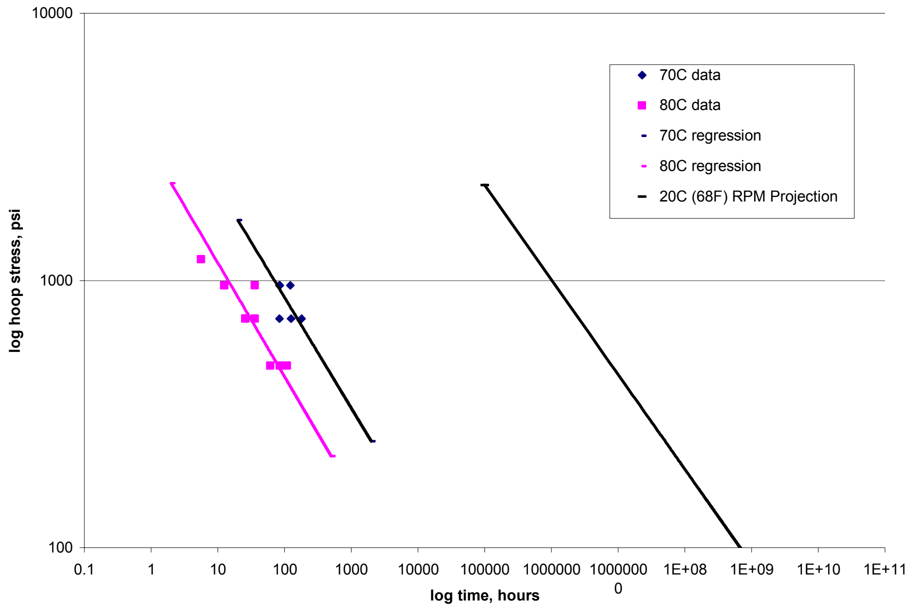

Figure 5: RPM Analysis of Control HDPE Corrugated Pipe

VII. RPM DATA FOR RECYCLED PIPE

Table II
RPM Data for 18" Recycled Corrugated HDPE Pipe

Temperature (°C)	**Pressure** (psig)	**Stress*** (psi)	**Failure Time** (hours)	**Failure Mode**
80	4	480	482	slit
			216	slit
			203	slit
	6	720	216	slit
			84	slit
			61	slit
	8	960	84	slit
			76	slit
			37	slit
70	6	720	755	slit
			252	slit
			84	slit
	8	960	932	slit
			828	slit
			289	slit
			85	slit
60	6	720	>300	on test
			>300	on test

*estimated stress at liner-junction interface based on FEA

Using the slit failure mode data at the various conditions and applying the RPM mathematical model, we arrive at the following coefficients and RPM projections:

$$\text{Log time} = -17.074 + 8353.1/T - 559.15*(\text{Log } P)/T.$$

Based on the 16 data points for this recycled pipe, the correlation coefficient was 0.62, which indicates there is a lot more scatter in these data for pipe containing recycled materials than those of the control pipe. The "lack of fit" F was 1.0636, and the probability associated with F was 0.38. The preliminary elevated temperature data and RPM projection at 20°C for this recycled pipe are shown graphically in Figure 6. The regression lines at 80°C and 70°C are based on the three coefficients of the RPM model for this recycled pipe lot. In this case again all failure modes are a slow crack that initiated in the notch between the liner and crown and propagated through the liner wall, just as was the case with virgin pipe. Note that for the recycled pipe there is more scatter in the data – this is due to the unknown PE materials that are in the recycled materials. These regression lines are the slope of the brittle or SCG curve – note that the slope for the recycled pipe is steeper, indicating greater sensitivity to the SCG failure mode. This 20°C regression line is now based on the three recycled pipe RPM coefficients, and represents the projected performance of this recycled corrugated HDPE pipe lot for the same failure mode – SCG through the liner wall. From this 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 20°C. Again, since the three RPM coefficients are known, any desired average ground temperature may be selected for this projection. By comparing the recycled 20°C regression line to the control 20°C regression line, it may be possible determine the effect of recycled materials on HDPE corrugated pipe.

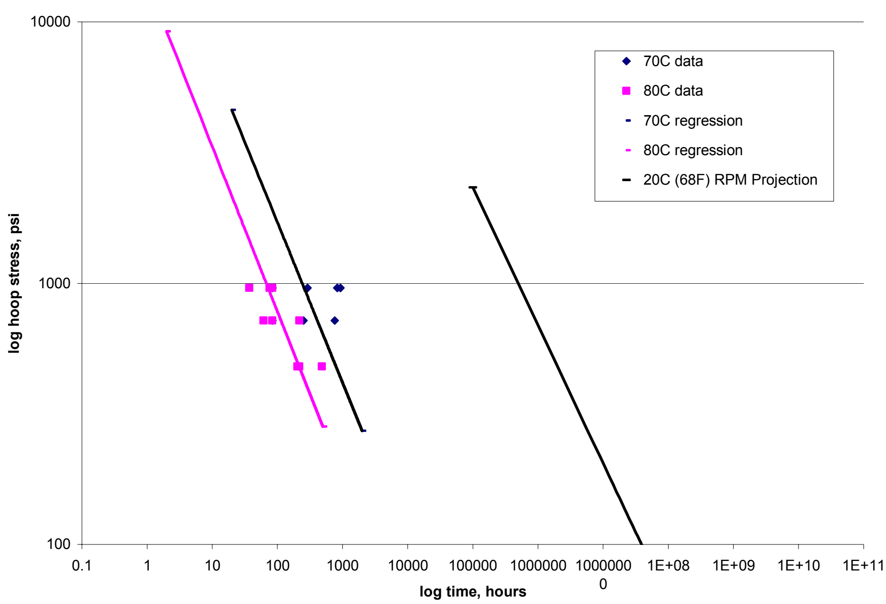

Figure 6: RPM Analysis of Recycled HDPE Corrugated Pipe

Based on these preliminary data developed, it appears that the Rate Process Method model provides a reasonable fit to the SCG failure modes 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 is planned to refine the extrapolations and further assess the suitability of this approach to modeling SCG failures in corrugated HDPE pipe.

VIII. CONCLUSIONS

The pipe ring test method appears to be a viable method to access the effect of recycled materials on corrugated HDPE pipe performance, 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. Finite element analysis (FEA) indicates the high stress area is 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. Rate process method (RPM) mathematical modeling conducted on control pipe ring specimens indicates a good correlation coefficient between the pipe ring data and the mathematical model. RPM testing on similar corrugated HDPE pipe containing recycled material had more scatter and a lower correlation coefficient. The advantages of the pipe ring test method are:

- Testing is conducted on the final extruded product
- The circumference of the pipe is tested rather than just a small test bar, therefore, the sample is more representative of the end-use product
- This method is applicable to any size corrugated pipe
- The failures modes are similar to testing solid wall pipe – ductile failures at high pressure and brittle (SCG) failures at low pressure
- 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 life 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
- The test method could also be used to determine the effects of secondary loads, such as bending and deflection.

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

- Testing of additional pipe sizes, constructions and materials to confirm broad applicability of the method.
- Analysis of field samples to confirm the ability of the pipe ring test method in generating the same failure mechanism as observed in field samples.
- FEA to correlate field stresses with the stresses in the pipe ring test method to enable performance projections at end-use conditions.

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