EVALUATE THE LONG-TERM STRESS CRACK RESISTANCE OF CORRUGATED HDPE PIPES

Y. Grace Hsuan, J-Y Zhang and W-K Wong
Department of Civil, Architectural and Environmental Engineering,
Drexel University, Philadelphia, USA

ABSTRACT

The 100-year stress crack resistance (SCR) of corrugated HDPE pipes was evaluated using a 600 mm diameter pipe. The SCR tests were performed on the finished pipe at the liner and junction locations. The notched constant ligament stress (NCLS) test (ASTM 2163) was used for the pipe liner assessment. For the pipe junction, a new test method was developed to challenge the junction geometry between the liner and corrugation. The test media was water to simulate the field condition of the drainage pipe and different elevated temperatures were utilized to accelerate crack growth rate. Two extrapolation methods, Popelar's Shift Method (PSM) and Rate Processing Method (RPM), were examined by comparing the predicted curve with experimental data. The results indicate that the RPM is a more reliable method, and has been adopted to perform the 100 years prediction. Utilizing the junction test data at 60, 70 and 80^{o}C, the brittle curve at 23^{o}C was predicted. The failure time was found well exceeded 100 years at the stress level of 3.4 MPa. Based on the results of the study, material specification for 100-year service life of corrugated HDPE pipes was established.

INTRODUCTION

In the United Sates, the design life of corrugated HDPE pipes in highway applications is generally 50 years. The material requirements for 50-year corrugated HDPE pipes are specified in the American Association of State Highway and Transportation Officials (AASHTO) M294 (2) which targets mainly on the pipe resin. Table 1 shows the required resin cell class of 335400C and their corresponding property values as defined and described in ASTM D 3350. For the SCR or slow crack growth resistance (SCGR) property, the specification has its own requirements instead of following ASTM 3350. The pipe resin is required to have failure time equal or greater than 24 hours using the test procedure according to the notched constant ligament stress (NCLS) test, ASTM F 2136. The hydrostatic design basis (HDB) is not required, since the resin is used for non-pressure pipes.

Recently, a 100 years design life was proposed by the industry prompting the Florida Department of Transportation (FDOT) to initiate a study on the long-term properties of corrugated HDPE pipes. The study consisted of two parts: field installation and material performance of the pipe (1). In the material performance part of the study, both SCR and oxidation resistance (OR) were addressed. The evaluated focused on the finished pipes instead of the pipe resins due to the uncertainty effects of carbon black, regrind and manufacturing process to those two properties(3, 4, and 5). In this paper, only the SCR portion of the study is presented.

Table 1 – Properties of Required Pipe Resin

Density	Melt Index	Flexural Modulus	Tensile Strength	SCGR	HDB
4	3	5	4	0	0
> 0.945 to <0.955 g/cc	<0.4 to 0.15 g/min	758 to <1103 MPa	21 to <24 MPa	Unspecified	Unspecified

Note: SCGR = slow crack growth resistance
HDB = hydrostatic design basis

TESTS TO EVALUATE SCR OF CORRUGATED HDPE PIPES

Pipe Liner Test

Due to the complex geometry profile of the corrugated pipe, SCR at different locations of the pipe has been investigated using the NCLS test (3, 4). It has found that specimen taken from pipe liner along the longitudinal direction with notch on the outer side of the liner exhibited the greatest susceptibility in stress cracking. Figure 1 shows the location of test specimens and the notched specimen. A test protocol based on the NCLS test for pipe liner was developed to be incorporated into a quality control and quality assurance (QC/QA) program so that the quality of the finished pipe can be consistently assessed (6, 7).

Pipe Junction Test

For the 100-year prediction of SCR, the notched liner specimen does not represent the field situation of the corrugated pipe, and would yield unrealistic results. The geometry of the junction between liner and corrugation creates stress concentration when the pipe is subjected to tensile stress, inducing the likelihood of cracking. Field investigations have also confirmed that most of cracking took place at the pipe junction (3). Therefore, a test targeting such locations was developed (7). Dumbbell shaped specimens are taken across the junction along the longitudinal direction of the pipe, as shown in Figure 2. For large diameter pipes, which have a wider valley, specimens will be taken from both junctions on two sides of the valley. There is no notching introduced to the test specimen. The applied stress is calculated based on the minimum liner thickness of the specimen. Cracking is initiated from defects of the material. Depending on the geometry of the junction, failure could take place at the junction or outside the junction.

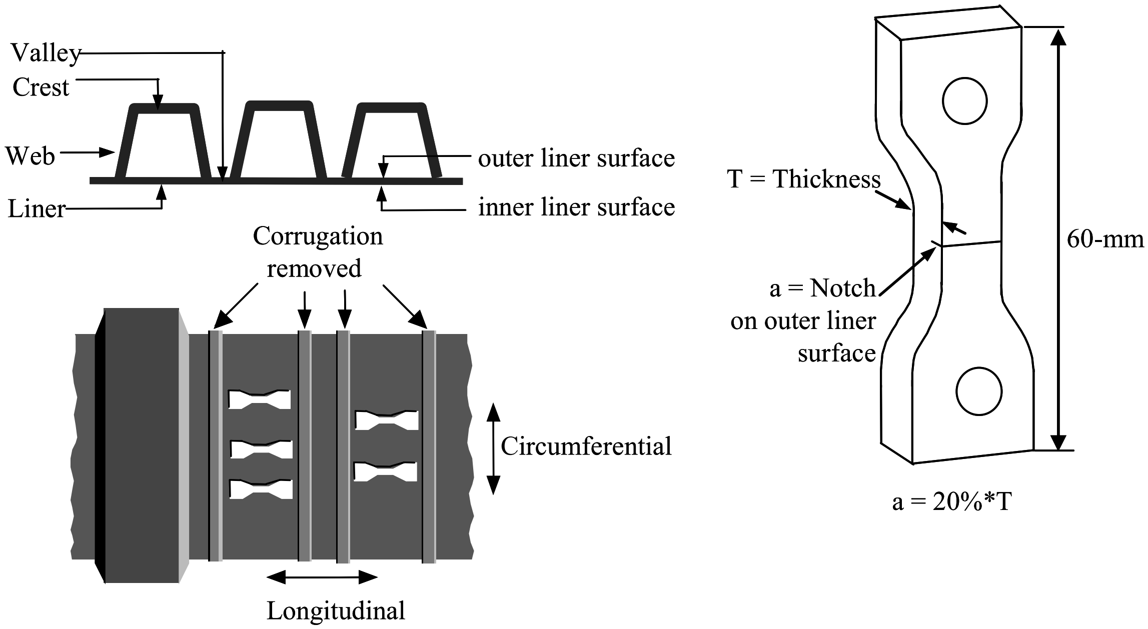

Figure 1 – Location and configuration of the NCLS test specimen on pipe liner

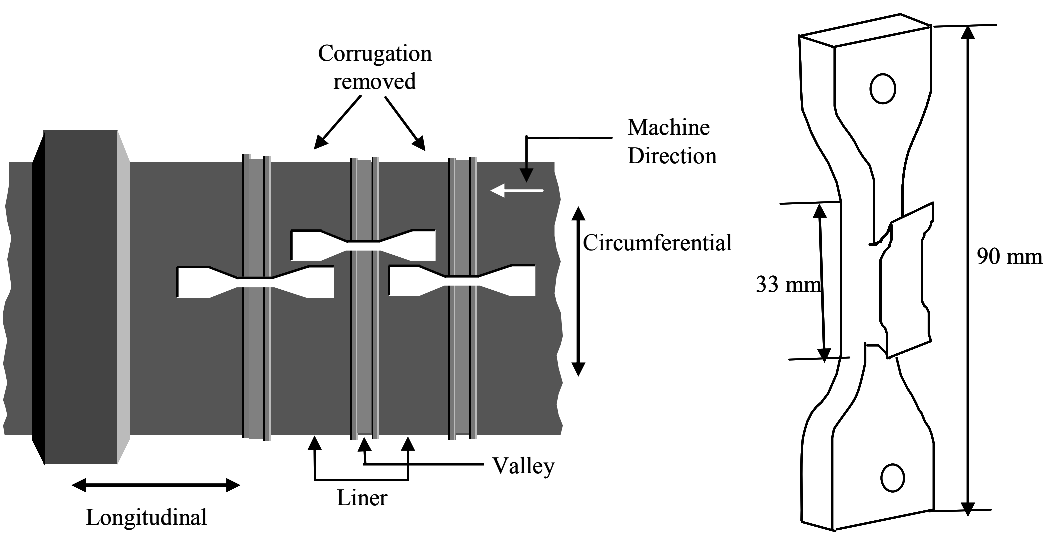

Figure 2 – Location and configuration of pipe junction specimens

TEST CONDITIONS

Since the focus of the study was to predict the long-term SCR performance of corrugated HDPE pipes in drainage application, tests were performed in water to simulate the field condition. Elevated temperatures were utilized to accelerate the crack growth rate. For the pipe liner material, tests were carried out at temperatures of 40, 60, 70, and 80°C; while 60, 70, and 80°C were used for pipe junction tests. Applied stresses used in the tests were low enough to ensure brittle failure occurring; the stresses ranged from 2 to 7 MPa for liner tests and 3.1 to 5.5 MPa for junction tests. At each stress level, three replicates were tested for the liner and minimum of five replicates for the junction test. The failure time of each specimen was recorded to the accuracy of ± 0.1 hour.

TEST MATERIAL

A 600 mm (24 in) corrugated HDPE pipe was used for both liner and junction tests. The pipe contains 2.5% carbon black with oxidative induction time (OIT) of 26 minutes according to ASTM D 3895. The pipe was cut into small pieces and compression molded into 2 mm (0.075 in) thick plaque using procedure described in ASTM D 4703. The properties of the compression molded plaque are listed in Table 2.

Table 2 – Material Property of the Tested Pipe

Property	Test Method	Value
Density* (g/cc)	ASTM D 793	0.950
Melt Index (g/10 min)	ASTM D 1238	0.2
Flexural Modulus (MPa)	ASTM D 790	830
Tensile Strength (MPa)	ASTM D 638	26
SCR (hours)	ASTM F 2136	31

*The density values were obtained by calculation using equation in ASTM D 3350.

SCR TEST RESULTS

The test data (liner and junction) are presented in a graphic form by plotting log stress against log failure time. The brittle curve at each temperature is determined using Equation (1).

$$log\, t = A + B\, log\, \sigma + e \tag{1}$$

Where:

σ = applied stress (MPa),
t = failure time (hour),
A, B = constants (*1/B* is the slope of the brittle curve),
e = error variable.

Figure 3 shows the brittle curves of NCLS-liner tests at four different temperatures, from 40 to 80°C (the fine dotted lines). The slopes of the curves are very similar at test temperatures from 40 to 70°C; however, a steeper slope is resulted at the 80°C test, as can be seen in Table 3. The variability of each set of three tests is within the precision of the test with coefficient of variation less than ± 15%. For pipe junction tests, the brittle curves at 60, 70 and 80°C are shown in Figure 4 (the fine dotted lines). As expected, failure times of the junction specimens are significantly longer than those of notched liner specimens under the same test condition. In addition, failure times among each set of test specimens vary greatly, particularly at 80°C. The coefficient of variation can be as high as ± 60%. As can be seen in Table 3, the slope of the brittle curve at 60°C is slightly lower than those at the two higher temperatures, while the slopes of junction curves are much shallower than those of the liner curves.

Table 3 – Parameters obtained from liner and junction test data

Material	Slope				Constants		
	80°C	70°C	60°C	40°C	A	B	C
Liner	-0.50	-0.45	-0.41	-0.44	-13.57	5649.93	-748.81
Junction	-0.22	-0.21	-0.17	NA	-22.55	9658.13	-1647.37

NA = not available

Note: For liner material the constants are calculated based on data at 60, 70 and 80°C. For junction material the constants are calculated based on data at 70 and 80°C.

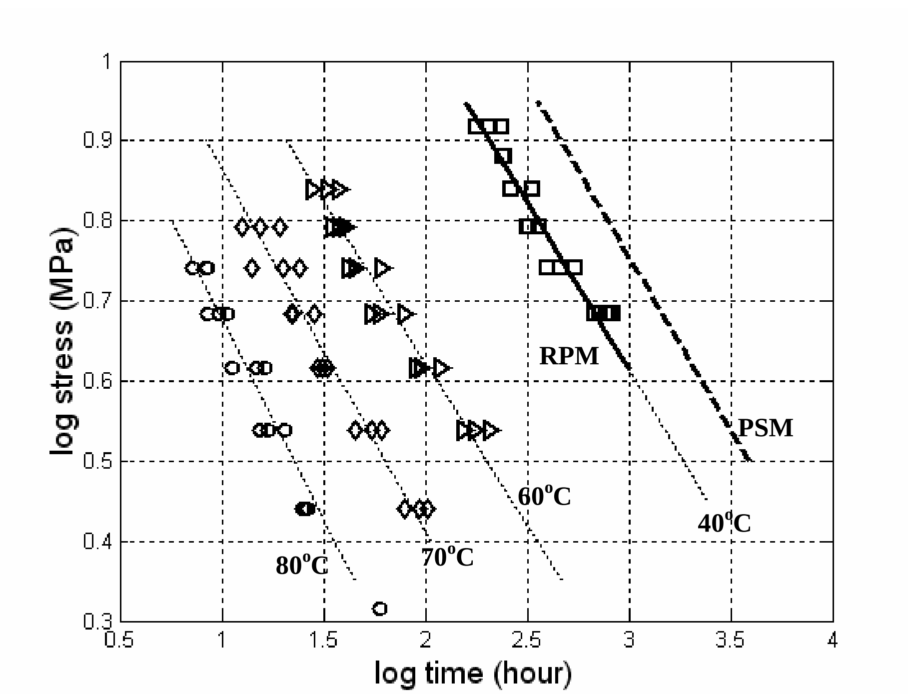

Figure 3 - Experimental and predicted brittle curves on notched pipe liner tests in water

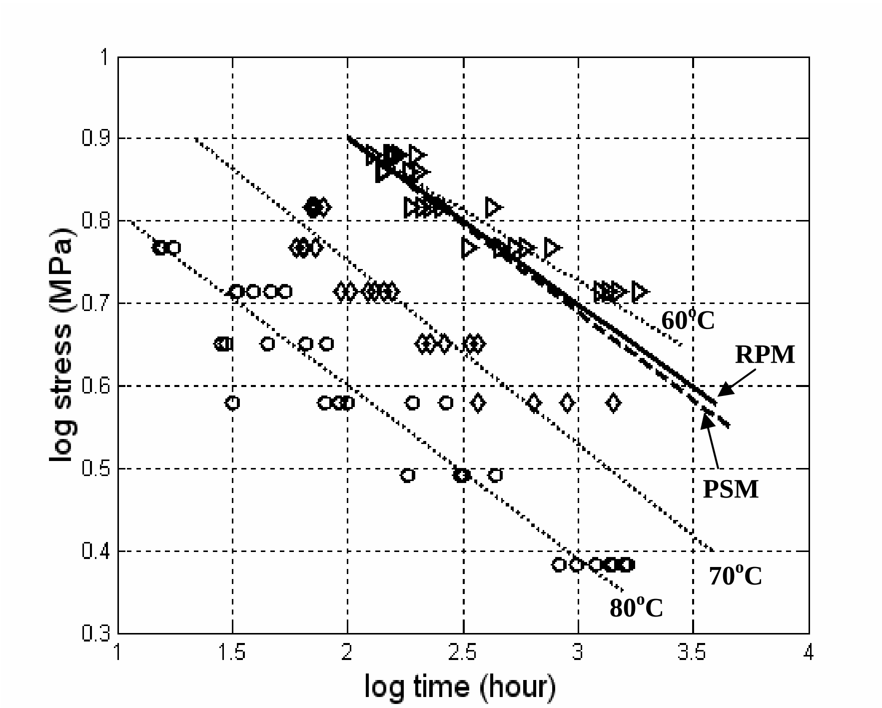

Figure 4 - Experimental and predicted brittle curves on pipe junction tests in water

DATA EXTRAPOLATION

Two extrapolation methods were evaluated in predicting data from elevated temperatures to lower temperatures. One was the Popelar's shift method (PSM) and the other was the Rate Process Method (RPM).

Popelar's Shift Method (PSM)

Based on many sets of ductile-to-brittle curves obtained from the burst test of gas pipes, Popelar, et al. (8) developed two factors to shift individual data in both time and stress, as expressed in Eqs. (2) and (3), respectively. However, the accuracy of these two shift factors has not been verified for corrugated HDPE pipes.

$$a_T = \exp[-0.109(T - T_R)] \tag{2}$$

$$b_T = \exp[0.0116(T - T_R)] \tag{3}$$

where:

a_T = horizontal shift function (time function)

b_T = vertical shift function (stress function)

T = temperature of the test, in K

T_R = target temperature, in K

Rate Process Method (RPM)

This method has been adopted by both ASTM D 2837 and ISO 9080 to analyze stress cracking data of pressure rated pipes. The method utilizes either a four coefficient model as suggested in the ISO standard or three coefficient model as stated in the ASTM procedure. In this paper, the three constant model (Eq. 4) is utilized to extrapolate the data. The three constants in Eq. (4) are determined using a least squares multi-variable regression analysis on data within brittle failure region. The equation with known constants can then be applied to predict the brittle curve at any temperature and stress under the same test conditions.

$$\log t = A + \frac{B}{T} + \frac{C \log \sigma}{T}$$

$$or \qquad (4)$$

$$\log \sigma = \frac{\log t - A - (B/T)}{C/T}$$

where:

t	= time to failure, in hours,
σ	= applied stress, in MPa
T	= test temperature, in K
$A, B, C, and D$	= constants

Data Extrapolation on Notched Liner Data

The two extrapolation methods described above are applied to data at 60, 70 and 80^{o}C of the NCLS liner tests to predict the brittle curve at 40^{o}C, which is then compared with the experimental data so that the validity of the methods can be assessed. For PSM, each data point at three elevated temperature tests is shifted to the target temperature of 40^{o}C using Eqs. (2) and (3). The shifted data are then analyzed by Eq. (1) to establish the brittle curve, as shown in Figure 3. In this case the method over predicts the failure times at 40^{o}C. The over predicted result was also obtained on a 900-mm corrugated HDPE pipe using the NCLS liner test at 60^{o}C (9).

On the other hand, the 40^{o}C predicted curve obtained from RPM overlaps the brittle curve created from the experimental data, as represented by the solid line in Figure 3. The predicted curve was generated by Eq. 4 with A, B and C calculated from data at 60, 70 and 80^{o}C. The three constant values are listed in Table 3.

Data Extrapolation on Junction Data

The two extrapolation methods are also applied to the pipe junction data at 70 and 80^{o}C in order to predict the brittle curve at 60^{o}C. The A, B and C constants in Eq. (4) are calculated and the values are included in Table 2. The two predicted curves are superimposed with the experimental data in Figure 4. For this pipe material, PSM and RPM yield very similar prediction. The predicted curves are close to the experimental data but with steeper slopes than the brittle curve obtained from the experimental data.

Predicting the SCR Service Life

In order to predict the 100 years SCR of corrugated HDPE pipes in the State of Florida, the field ambient temperature and the tensile stress generated during the service of the pipe must be defined. Based on records of two weather stations, the annals average temperature in the Florida peninsula is 23°C, while higher temperature is experienced in the Key region. Regarding the maximum tensile stress in the pipe, McGrath (1) analyzed both longitudinal and circumferential tensile strains of the pipe under 5% vertical deflection limit, and computed the long-term tensile strain being less than 1.6%. The corresponding tensile stress was calculated to be 2.1 MPa using the long-term modulus of 138 MPa. After considering a factor safety of 1.6, the long-term tensile stress in the pipe was defined to be 3.4 MPa.

For the extrapolation method, the evaluation performed on both notched liner and junction of the corrugated HDPE pipe indicates that RPM would be a more reliable method than PSM to analyze the stress cracking data. Furthermore, RPM has been adopted by the ASTM D 2837 and can be readily incorporated into a materials specification.

Since majority of cracking in the field had been found to take place at the pipe junctions (3), the 100-year SCR should be assessed using the junction data. The A, B, and C constants in Eq. (4) are calculated using data at 60, 70, and 80°C. Eq. 4 with known constants is then used to establish the brittle curves at three tested temperatures, as well as the predicted brittle curve at 23°C, as shown in Figure 5. The dotted lines displayed in Figure 5 represent the 97.5% lower confidence at each temperature using equations described in ISO 9080. The predicted failure time under 3.4 MPa well exceeds 100 years at 23°C, even considering the 97.5% lower confidence. Therefore, the 600 mm tested pipe should not exhibit cracking at the junction during the 100-year service life as long as the vertical deflection remains at 5%.

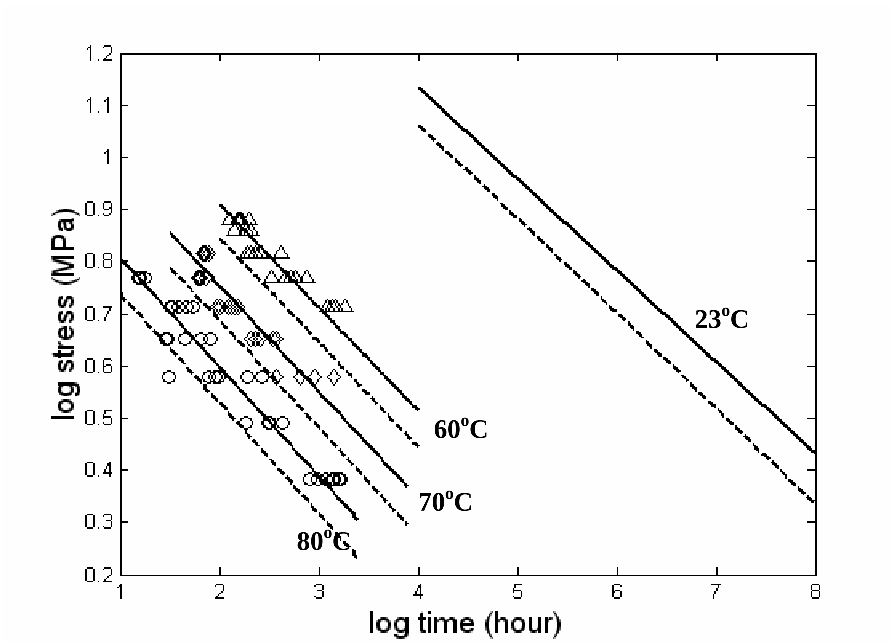

Figure 5 – Predicting the junction brittle curve at 23°C

SPECIFICATION

In result of this study, an interim specification was developed and implemented by the State of Florida to evaluate the quality of pipes that require 100-year service life. The portion of the interim specification that is related to stress crack properties is shown in Table 4. Each test bases on go-or-no-go criterion under specific test conditions.

Table 4 – Interim Specification for Long-Term Performance of Corrugated HDPE Pipes

Stress Crack Resistance of Pipes			
Pipe Location	Test Method	Test Conditions	Requirement
Pipe Liner	FM 5-572, Procedure A	10% Igepal solution at 50°C; 600 psi applied stress with 5 replicates	Average failure time of the pipe liner shall be ≥ 18 hours; no single value shall be less than 12 hours.
Pipe Corrugation* (molded plaque)	ASTM F 2136	10% Igepal solution at 50°C; 600 psi applied stress	Average failure time shall be ≥24 hours; no single value shall be less than 17 hours.
Junction**	FM 5-572, Procedure B and FM 5-573 ASTM D 2837	Test temperature 80°C and applied stresses of 650 and 450 psi. Test temperature 70°C and applied stress of 650 psi; 5 replicates at each stress level	Calculate three constants Failure time at 500 psi at 23°C ≥ 100 years (95% statistical confidence)
		Single Test: Test temperature 80°C and applied stress of 650 psi. 5 replicates	The failure time must be equal or greater than the calculated value using the three constants from the three point test

Note: FM= Florida Method of Test.
* Required only when corrugation resin is different than liner resin.
** A higher test temperature (90°C) may be used if supporting test data acceptable to the State Materials Engineer is submitted and approved in writing.

SUMMARY

The 100-year SCR of corrugated HDPE pipes was evaluated using a 600-mm diameter pipe. The SCR tests were performed on pipe liner and junction at elevated temperatures from 40 to 80°C. Test data were used to assess the validity of PSM and RPM, and found that RPM yielded a good prediction for both notched liner and junction data. The RPM predicted failure time at 23°C under tensile stress of 3.4 MPa was found well over 100-year. Specification was also developed based on the finding of the study to ensure SCR properties of the pipe for 100-year service life.

ACKNOWLEDGEMENT

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