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STRESS CRACK RESISTANCE OF RECYCLED AND VIRGIN HDPE CORRUGATED PIPE FOR TRANSPORTATION INFRASTRUCTURE APPLICATIONS

Khanh Q. Nguyen[1,2,*], Khaled Mohamed[1], Patrice Cousin[1], Mathieu Robert[1], and Brahim Benmokrane[1]

[1] Dept. of Civil Engineering, Univ. of Sherbrooke, Sherbrooke, QC, Canada J1K 2R1
[2] Quoc.Khanh.Nguyen@Usherbrooke.ca
* Corresponding author

Abstract: As the use of recycled high-density polyethylene (HDPE) corrugated pipes is interested in road-drainage systems, their long-term properties need to be clarified. Recently, a research project was initiated at the University of Sherbrooke in collaboration with Quebec's Ministry of Transportation (MTQ) to evaluate the durability of recycled and virgin HDPE pipes. The present study presents the stress crack resistance (SCR) part of the project. Notched specimens were cut from two corrugated HDPE pipe liners 900 mm in diameter for SCR tests. The SCR tests were performed in water at three different combinations of pressure/temperature of 650 psi/80^{0}C, 450 psi/80^{0}C, and 650 psi/70^{0}C according to FDOT FM5-573. Two extrapolation methods, Popelar's Shift Method (PSM) and Rate Process Method (RPM), were used to generate a failure curve for each product. The results show that the RPM method is more reliable and is used to estimate 100 years of pipe lifetime. At service conditions of 10^{0}C and 500 psi, recycled pipes guarantee 100 years of service life as virgin pipes.

Keywords: High-density polyethylene (HDPE) pipes; stress crack resistance (SCR); Popelar's Shift Method (PSM) and Rate Processing Method (RPM); recycled pipes; 100-year service life.

1 INTRODUCTION

High-density polyethylene (HDPE) pipe is one of the materials of interest for road-drainage systems because it is lightweight, corrosion-resistant materials, flexible, easy to install, and entails low maintenance costs rather than steel and concrete pipes (Spalding and Chatterjee 2017, PPI 2008, PPI 2015, Petroff 2013, Rubeiz 2004, Ortega et al. 2004). While the initial cost-saving is over 20% for corrugated HDPE pipes compared to reinforced concrete pipes. As compared to other pipes, the overall cost-saving of 30% for HDPE pipes is found (Pluimer 2016). Therefore, HDPE pipes are the best materials used in road-drainage systems. The long-term service life of HDPE is introduced through three stages of aging (Hsuan and Koerner 1995, Hsuan and Koerner 1998). These are ductile failure (stage I), brittle failure (stage II and III). In stark contrast to pressure pipes, stage I failure does not introduce because they are not subjected to high enough tensile strains. On the other hand, stage III failure due to chemical/molecular degradation may be prevented by ensuring sufficient antioxidants present in pipes. Hence, Stage II of failure due to slow crack growth (SCG) is the primary concern for corrugated pipes in road-drainage systems. In general, the slow crack growth involves brittle cracking through two phases (1) crack initiation and (2) crack propagation phases (Krishnaswamy 2005). The damage zone of the crack initiation phase is dominated by a single craze and structural voids, while the crack propagation phase is a function of the stress crack resistance (SCR) of pipes.

Currently, corrugated HDPE pipes used in road-drainage systems are usually made from virgin resins. However, an increase in the use of HDPE in consumer products (detergent bottles and milk jugs) has become a significant source of recycled materials for pipes. As compared to virgin pipes, the use of recycled pipes is more sustainable and cost-effective. A decrease in carbon footprint can be obtained with products that contain recycled content (Dormer et al. 2013). Recycling plastic can reduce the use of raw materials, energy requirements, water consumption, and greenhouse-gas emissions in the production process (Korhonen and Dahlbo 2007, Na et al. 2018). Therefore, the stress crack resistance of recycled HDPE pipes must be evaluated to estimate their service lifetime. There are several common methods for evaluating the SCR of HDPE pipe, such as the environmental stress crack resistance (ESCR) in (ASTM D1693-15e1 2015), the Pennsylvania notched test (PENT) in (ASTM F1473 2018), the Notched Constant Ligament Stress (NCLS) in (ASTM F2136 2018), the Un-Notched Constant Ligament Stress (UCLS) in (ASTM F3181 2016), and the Florida Test method in (FM 5-573 2008). However, each method has its own advantages and disadvantages (Nguyen et al. 2021). To avoid the incubation environment's aggressive and long testing times, the Florida Test method in (FM 5-573 2008) is often recommended.

Very little has been found in the literature about the stress crack resistance and predicting the service life of recycled HDPE in road-drainage systems (Thomas 2011, Pluimer et al. 2015, Pluimer 2016, Pluimer et al. 2018, Shaheen 2018). Recently, (AASHTO M924 2018) and (ASTM F2306/F2306M 2019) are updated to bring recycled HDPE in line with specified requirements according to NCHRP Research Report 870 (Pluimer et al. 2018). However, with a diversity of production and installation standards, the long-term service life of HDPE pipes depends on the conditions at each installation area. The aim of the present study is to evaluate the stress crack resistance of recycled and virgin HDPE pipes produced from local manufacturers by the Florida Test method. The results are then used to estimate the 100-year service life of pipes.

2 MATERIALS AND TEST CONDITIONS

2.1 Materials

Two new corrugated HDPE pipes from the same North American manufacture used for non-pressure road-drainage systems (e.g., storm drainage, storm sewers) were examined in the present study. They are pipes with a density greater than 0.940 g/cm^3 (ASTM D3350 2014) which one pipe manufactured with recycled resins (A-R) and one with virgin resins (A-V). The diameter and length of each pipe were 900 mm and 3000 mm, respectively. The properties of pipes are listed in Table 1.

Table 1: Material property of tested pipe

Property	Test Method (ASTM)	A-R	A-V
Density (g/cm^3)	D792 2016	0.988	0.977
MFI (g/10 min)	D1238 2013	0.103	0.077
10^{-3} M_n molecular weight (gmol^{-1})	-	11.9	7.3
10^{-3} M_w molecular weight (gmol^{-1})	-	405	323
CB (%) content	D5805-00 2019	3.0	2.8
Hardness (HD)	-	56	55
Mass loss (^{0}C)	E2550 2017	390	375
Tensile strength at yield (MPa)	D638 2014	25.12	23.58

ASTM: American Society for Testing and Materials; MFI: Melt flow index; CB: carbon black.

To investigate the stress crack resistance, small specimens were punched directly onto the pipe liner using a stainless-steel die (Figure 1a). The test specimens have the same geometry used for (ASTM F2136 2018) (Figure 1b). Notch depth must be controlled to 20% of the average thickness of pipe liner.

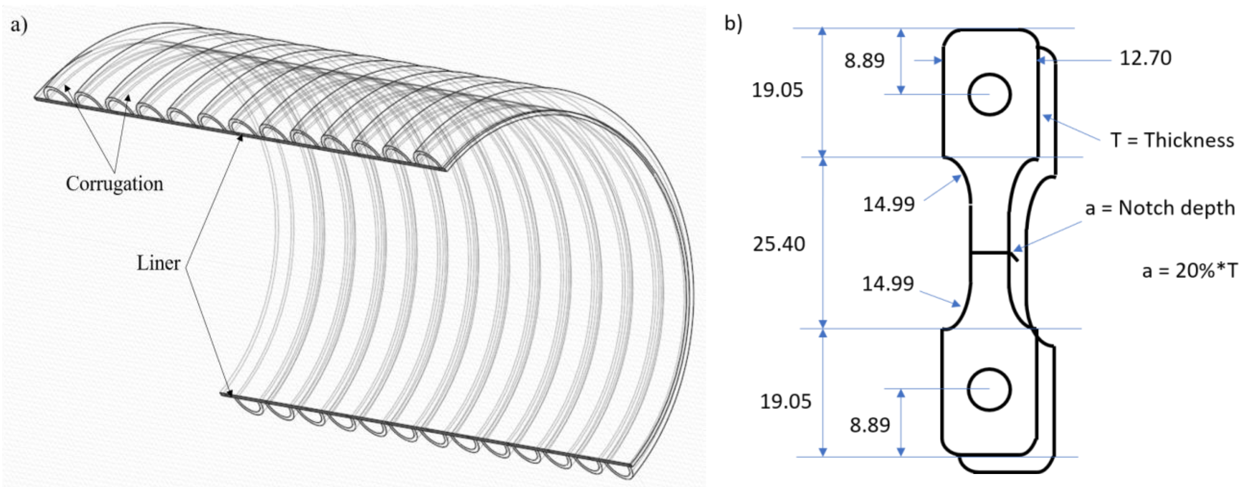

Figure 1: a) Sectional view of HDPE pipe b) Specimen geometry (mm)

2.2 Test conditions

The first time presented by (Hsuan and McGrath 2005), the Florida Test Method uses the water environment instead of the surfactant solution (10 vol.% Igepal) as in the NCLS method. In the present study, the service temperature of these pipes is around 10^0C. As discussed earlier, the impact of the surrounding environment (e.g., chemical solutions, humidity...) do not significantly affect pipeline degradation. The stress crack resistance (SCR) of HDPE pipes is evaluated by using data obtained from the (FM 5-573 2008), procedure C. This test method measured the failure time of test specimens at 650 psi/70^0C, 650 psi/80^0C, and 450 psi/80^0C. At least five repetitions were performed. The test data was then shifted to generate a master curve based on the Popelar's Shift Method (PSM) and Rate Process Method (RPM) equations.

3 ANALYTICAL METHODS

For predicting the service life of pipes, two extrapolation methods are used to extrapolate data from high temperatures to service temperatures: Popelar's Shift Method (PSM) and Rate Process Method (RPM).

3.1 Poperlar's Shift Method (PSM)

Based on numerous studies of MDPE and HDPE gas pipes, (Popelar et al. 1991) developed two factors (horizontal and vertical) to shift data points in both time and stress axes, as described in Eqs. (1) and (2), respectively. The horizontal shifting (a_T) was related to the time-temperature superposition principle while the vertical shifting (b_T) was obtained due to the effect of temperature on crystallinity. The failure time at a high temperature is shifted to a lower service temperature, the shift factor a_T is used. Whereas the shift factor b_T is used to shift the stress at a high temperature to a lower service temperature. Testing materials at three different combinations of pressure/temperature allows the shifting of three data points to generate a master curve at service temperature (e.g., 10^0C).

[1] a_T (Time Shift Factor) $= \exp[0.109(T-T_R)]$

[2] b_T (Stress Shift Factor) = exp[0.0116(T-T_R)]

where, a_T is the horizontal shift factor, b_T is the vertical shift factor, T is the temperature (K), and T_R is the reference temperature (service temperature) (K).

3.2 Rate Process Method (RPM)

The fundamental theory for the rate process method (RPM) developed from the Arrhenius principle of time-temperature superposition. This method is widely used and has been adopted by both (ASTM D2837-13e1 2013) and (ISO 9080 2012) to evaluate the stress crack resistance of polyethylene pipes. The ISO 9080 consists of a four-coefficient model, whereas a three-coefficient model is used to extrapolate the data in ASTM D2837. In the present study, three coefficients as described in Eq. (3) are determined by using a least-squares multivariable linear regressions method. A failure curve at any temperature and stress is achieved using Eq. 3 with three known coefficients.

[3] $\log(t) = A + B/T + C.\log(\sigma)/T$

where, t is the time to failure (hours), σ is the applied stress (psi), T is the test temperature (K), and A, B, and C are constants.

4 RESULTS AND DISCUSSIONS

The Florida Test Method (FM 5-573) was performed on specimens that had been immersed in a water environment at 650 psi/70^{0}C, 650 psi/80^{0}C, and 450 psi/80^{0}C. The average failure time of two corrugated HDPE pipes (A-R, A-V) is summarized in Table 2.

Table 2: Average failure time of corrugated HDPE pipe

Specimen	Test Conditions	Average Failure Time (h)	Standard Deviation	Coefficient of Variation
A-R	450 psi/80^{0}C	10.28	0.760	0.074
	650 psi/80^{0}C	4.12	0.217	0.053
	650 psi/70^{0}C	17.70	0.529	0.030
A-V	450 psi/80^{0}C	132.08	12.028	0.091
	650 psi/80^{0}C	119.24	47.179	0.396
	650 psi/70^{0}C	387.54	140.981	0.364

In the present study, the temperature of service for two corrugated HDPE pipes is 10^{0}C. According to (Hsuan and McGrath 1999)'s research, the failure time at 500 psi should be greater than 100 years. Based on failure time in Table 2, two extrapolation methods are used to predict 100 years SCR of corrugated HDPE pipes.

4.1 Poperlar's Shift Method (PSM)

Using the shift factors in Table 3, the failure times of the A-R and A-V pipes at 80^{0}C and 70^{0}C are shifted to 10^{0}C, as shown in Table 4.

Table 3: Shift factors for 80^{0}C and 70^{0}C to 10^{0}C

Shift Factors	Time Shift Factor (a_T)	Stress Shift Factor (b_T)
Shift factors for 80^{0}C to 10^{0}C	2059.050	2.252
Shift factors for 70^{0}C to 10^{0}C	692.287	2.006

Table 4: Average failure test data shifted to 10^0C

Specimen	Test Conditions	Shifted Stress (psi)	Shifted Time (psi)	Shifted Stress - Log (psi)	Shifted Time - Log (psi)
A-R	450 psi/80^0C	1013.584	21167.034	3.006	4.326
	650 psi/80^0C	1464.065	8483.286	3.166	3.929
	650 psi/70^0C	1303.714	12253.472	3.115	4.088
A-V	450 psi/80^0C	1013.584	271959.327	3.006	5.435
	650 psi/80^0C	1464.065	245521.124	3.166	5.390
	650 psi/70^0C	1303.714	268288.741	3.115	5.429

4.2 Rate Process Method (RPM)

To predict the failure time with 97.5% lower confidence at 10^0C and 500 psi, three coefficients (A, B, and C) are solved using all data points in Table 2. A least-squares multivariable linear regression method is used to determine these coefficients as shown in Table 5. In other words, the coefficients A, B, and C can be solved by using the matrix algebra as shown in Eqs. (4) and (5) for A-R, A-V pipes, respectively.

$$[4] \quad \begin{pmatrix} \log(10.28) \\ \log(4.12) \\ \log(17.70) \end{pmatrix} = \begin{pmatrix} 1 & 1/353 & \log(450)/353 \\ 1 & 1/353 & \log(650)/353 \\ 1 & 1/343 & \log(650)/343 \end{pmatrix} \begin{pmatrix} A \\ B \\ C \end{pmatrix}$$

$$[5] \quad \begin{pmatrix} \log(132.08) \\ \log(119.24) \\ \log(387.54) \end{pmatrix} = \begin{pmatrix} 1 & 1/353 & \log(450)/353 \\ 1 & 1/353 & \log(650)/353 \\ 1 & 1/343 & \log(650)/343 \end{pmatrix} \begin{pmatrix} A \\ B \\ C \end{pmatrix}$$

Table 5: Coefficients for RPM method

Specimen	Coefficient	Value	Standard Deviation	t-value
A-R	A	-21.112	0.514	-41.075
	B	10135.532	238.371	42.520
	C	-876.771	32.642	-26.850
A-V	A	-15.645	2.729	-5.732
	B	6658.868	1265.816	5.261
	C	-146.218	173.340	-0.844

4.3 Predicting SCR service life

A comparison between the PSM and RPM predicted failure time and brittle curve slopes for recycled (A-R) and virgin (A-V) pipes is shown in table 6 and in Figures 2a and 2b.

Table 6: Average failure test data shifted to 10^0C

Specimen	Slope		Y-intercept		Predicted time to failure at 500 psi, 10^0C	
	PSM	RPM	PSM	RPM	PSM	RPM
A-R	-0.4067	-0.3228	4.7686	4.7456	14 years	250 years
A-V	-2.7726	-1.9355	18.1166	15.2603	42 years	353 years

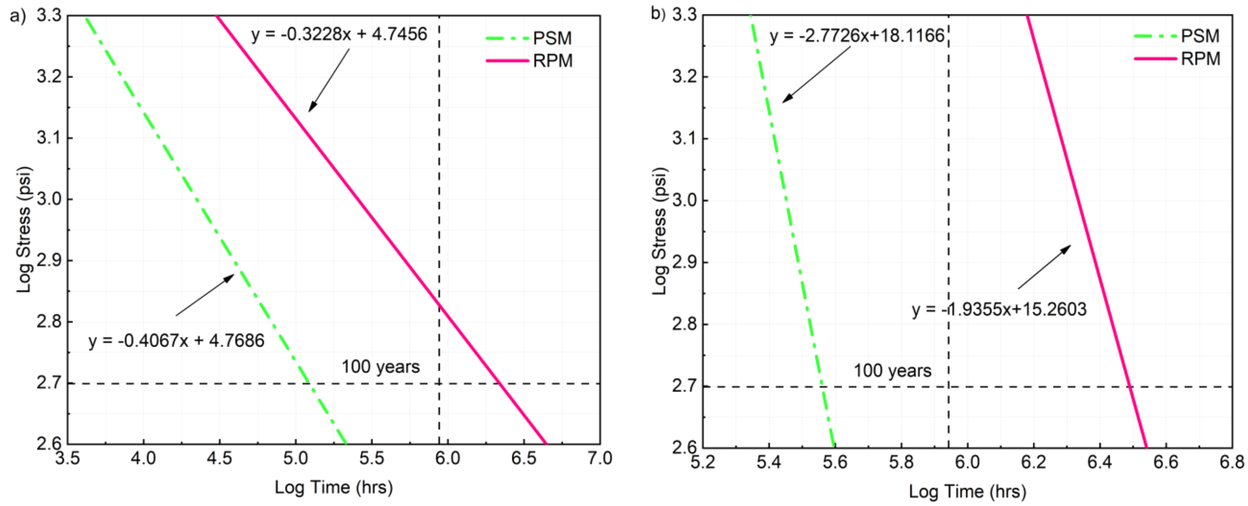

Figure 2: Master curve at 500 psi, 10^{0}C for PSM and RPM methods a) A-R b) A-V

Table 6 shows that the predicted failure time via the RPM is longer than via the PSM method. The results indicate that the recycled pipe (A-R) meets the 100-year service life applications as the virgin pipe (A-V). This result is similar to the previous studies (Hsuan et al. 2007, Pluimer 2016). The RPM method is more reliable than PSM to analyze the stress cracking data of corrugated pipes.

5 CONCLUSION

The 100-year service life of recycled and virgin HDPE corrugated pipes for transportation infrastructure application was investigated. The SCR tests were performed on pipe liner in water at three different combinations of pressure/temperature of 650 psi/80^{0}C, 450 psi/80^{0}C, and 650 psi/70^{0}C according to FM5-573. Both PSM and RPM methods were used to evaluate the stress crack resistance of pipes. It is found that the RPM method is more reliable rather than the PSM method. At service conditions of 500 psi and 10^{0}C, the recycled pipe meets the 100-year service life applications as the virgin pipe.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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