CAAP Quarterly Report

Date of Report: February 28, 2021

Prepared for: U.S. DOT Pipeline and Hazardous Materials Safety Administration

Contract Number: 693JK32050001CAAP

Project Title: Modeling Slow Crack Growth Under Thermal and Chemical Effects and Accurate NDT of Cracks for Fitness Predictions of Polyethylene Pipes

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For quarterly period ending: February 28th, 2021

Business and Activity Section

(a) Contract activity

No modifications were made to the contract.

(b) Status update of past quarter activities

During the second quarter (December 2020 – February 2021), we conducted literature review of slow crack growth models at room temperature and under chemical exposure conditions for high-density polyethylene (HDPE). We reviewed the literature to evaluate how chemical exposure and temperature affect slow crack growth (SCG) in HDPE. Data from existing publications was extracted and stored for future model fitting. To further investigate the slow crack growth in HDPE, we conducted preliminary testing with PE100 under room temperature conditions with ASTM D638 standard. We plan to use the data collected from preliminary testing to help develop a slow crack growth model for HDPE.

We have also investigated the viscoelastic effect of HDPE material in the literature. Our preliminary study indicates that it will be relevant to incorporate viscoelastic effects for ultrasound waves for a frequency of a few MHz. We have found the attenuation coefficient for ultrasonic propagation in HDPE. We have started to evaluate the Prony series viscoelastic model in ABAQUS to model the attenuation.

(c) Cost share activity

Partial support for graduate student tuitions and research staff were provided by Brown University School of Engineering as per the cost share agreement.

(d) Task 1: Modeling slow crack growth in HDPE under thermal and chemical effects

Task 2: Ultrasonic and machine learning based accurate crack measurement method for HDPE

1. Background and objectives in the 2nd quarter

1.1 Background

The phenomenological model [1] proposed by Brown and Lu addressed the slow crack growth (SCG) rate in polyethylene material at room temperature without environmental effects. The existing SCG model with environmental impacts proposed by Ge et al [2] focuses on numerical simulation of the SCG when polyethylene material is exposed to diesel fuel in room temperature conditions. The majority of the gas transportation pipelines are exposed to hydrocarbon chemicals in controlled temperature and pressure. As a result, we looked into additional models and experimental data that address how hydrocarbon chemicals impact SCG in different temperature conditions.

The HDPE material in pipeline applications requires long-term reliability and integrity [3]. To better understand the SCG phenomena within a shorter experimental time span, acceleration methods for the SCG in HDPE are required. Accelerated failure testing methods proposed by Schilling et al. have been used [4][5] to study how environmental factors can impact SCG and material failure. As shown in Figure 1, the elongation of the HDPE material at different temperature conditions was recorded and visualized in a single plot by increasing the exposure environment's temperature. In Figure 2, the experimental data by Schilling et al. [4] provided valuable data on how different chemical solutions and temperatures can impact the SCG process.

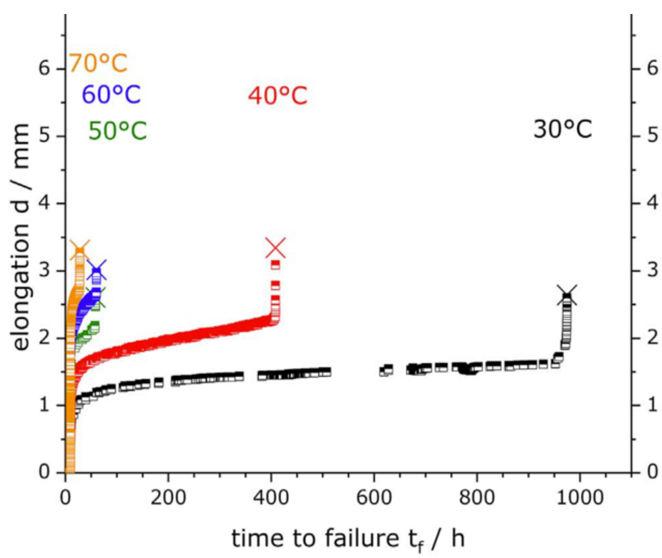

Figure 1. Example of temperature affecting failure time [4].

Most published literature on HDPE utilized either a single edge notched tensile test (SENT) [7][8] or a full notched tensile test (FN) [9][10][11] to evaluate the SCG under environmental stress conditions. The notched specimens can be used to measure the crack tip opening displacement, crack size, crack angle, and total elongation of SCG in HDPE for quantitative modeling. For single notched specimens (Figure 3a), crack propagation can be easily observed and measured in real-time. Full notch specimens are better for exploring crack propagation within the material under relatively higher triaxial load conditions (Figure 3b). The primary method of measuring the displacements in the test samples mentioned above is by using extensometers[4][12][13][14][15]. Traditional extensometers are used in combination with Instron testing to measure the elongation of the sample. In slow crack growth, the crack tip opening displacement and crack size are difficult to measure precisely with traditional extensometers. As a result, the MTS Bionix system with the digital imaging correlation camera (DIC) will be one of the testing method sto measure the SCG in HDPE test specimens. In published literature by Schilling et al.[4], the creep tests were conducted at stresses around 2 - 12 MPa (resulting in 9e-8 s-1 to 7e-5 s-1 strain rate). These tests lasted anywhere from four hours to over four months. To better observe the SCG phenomena under long-term creep conditions, a customized long-term creep test setup is required to measure all necessary parameters for subsequent physical model development.

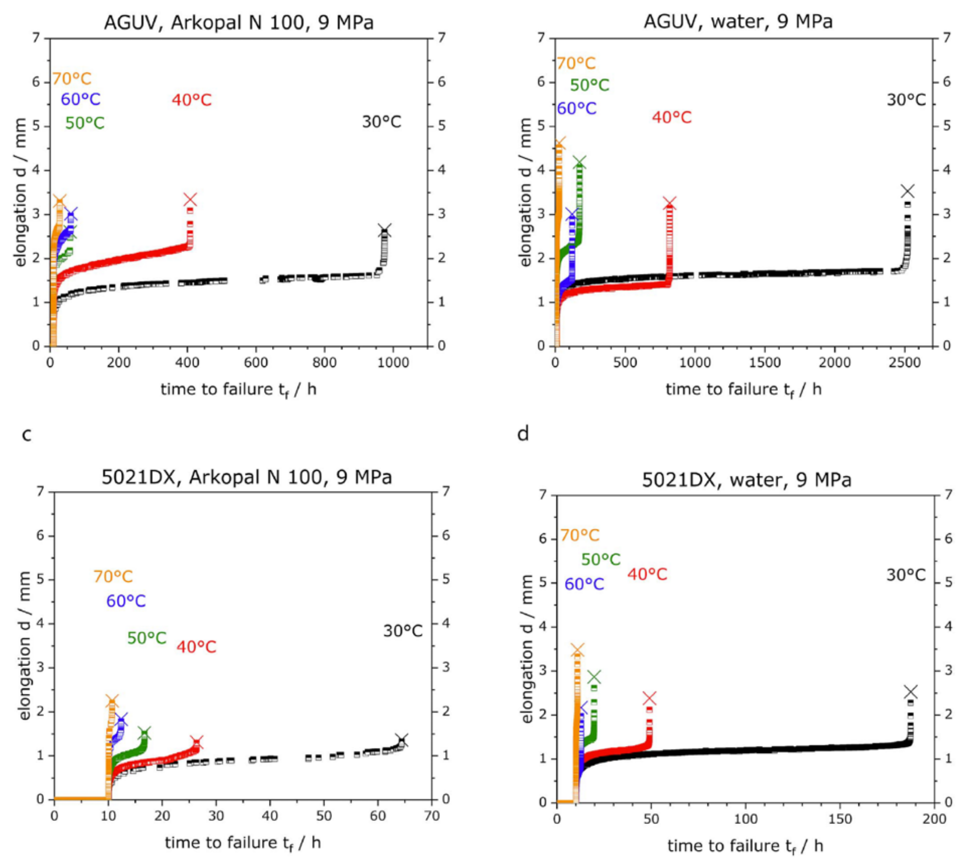

Figure 2. Example of temperature and chemical exposure affecting failure time [4].

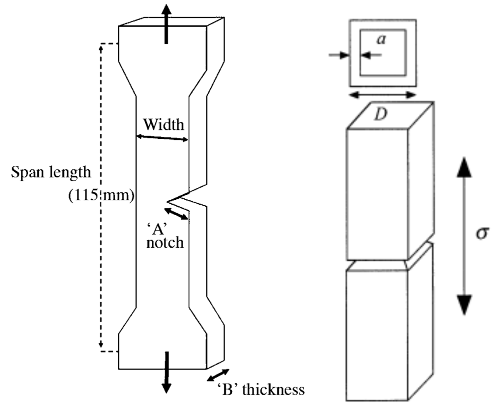

Figure 3. (a) Examples of a single edge notch tensile test (SENT) specimen [34]; (b) A full notch test (FNT) specimen [4].

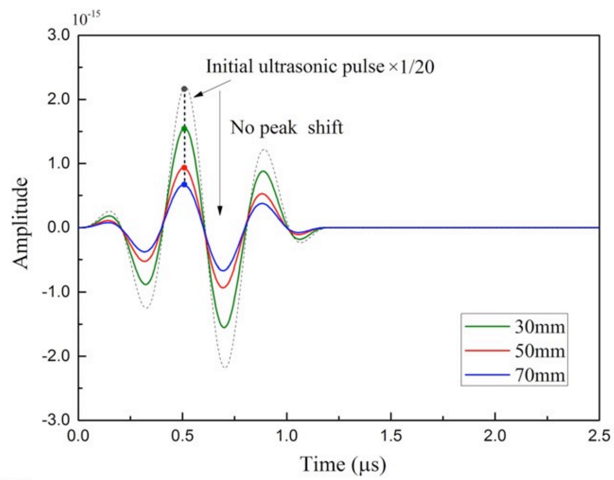

Figure **4**. Ultrasonic wave attenuation in HDPE from reference [3].

Viscoelasticity is a characteristic property of most polymers. Unlike purely elastic material, energy is dissipated in such material and may lead to the attenuation of ultrasound waves. However, the degree of this effect is not obvious. For ultrasound with a frequency of a few MHz, the characteristic time is of order of $10^{-6} – 10^{-7}$ second which may be much smaller than characteristic time of viscoelastic effect. We found that many publications gave a characteristic time of a few hundred to thousand seconds based on long term creep test [37][38], which does not affect ultrasound propagation. In this paper, a linear relation between attenuation coefficient and frequency is given and it is suggested that attenuation should be considered in simulations based on experimental results [3]. Attenuation is visualized in Figure 4, taken from the reference.

1.2 Objectives in the 2nd quarter

Task 1: We aimed to develop necessary experimental protocols for conducting the preliminary experiments in the next quarter. By bridging the literature reviews from the previous quarter, we aimed to develop protocols and build in-house testing setups for HDPE experimental sample preparation, long-term creep testing, thermal exposure testing, and chemical exposure testing. Preliminary data analysis with the published SCG model was performed. The second quarter was an important experimental set-up and protocol preparation phase for the preliminary experiments during the next quarter.

Task 2: We aimed to investigate the viscoelastic effect of HDPE and its role in ultrasonic propagation.

2. Experimental program in the 2nd quarter

2.1 Experimental design

We have started to develop a preliminary experimental setup to evaluate how environmental factors impact SCG phenomena in HDPE. HDPE sample specimens used for initial experiments were made following the American society of testing and material (ASTM) A638 type 5 standard for plastic testing (Figure 5). All sample specimens were machined with the Tormach 15L CNC machine in-house. To perform the long-time creep test in the coming quarter, we have started to developed an in-house long-term creep testing rack to secure sample specimens without damage. The in-house thermal and chemical exposure chambers were also developed and they are being tested. The experimental design objective in the 2nd quarter was to identify the best experimental protocols and setups before the preliminary experiment in the coming quarter.

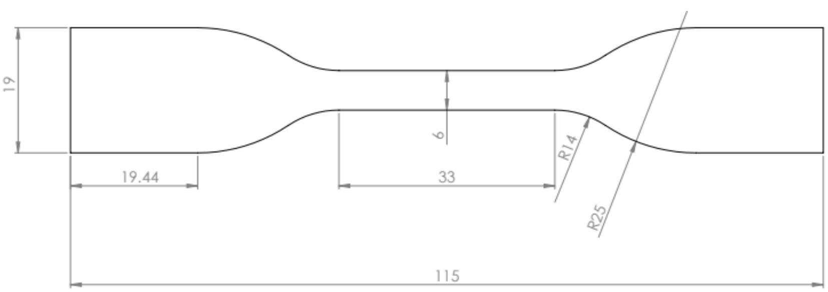

Figure 5. ASTM A638 type 5 sample dimension [35].

2.2 Computational setup

Preliminary computations

We extracted experimental SCG data under chemical exposure, temperature, and stress conditions from publication by Schilling et al. [4]. The data extracted from the publication with open source software WebPlotDigitizer are the time of failure, crack tip opening displacement, temperature, stress, and chemical exposure category. All raw data files were saved in .csv format for subsequent model fitting with MATLAB. We aim to evaluate existing and new models using this extracted data.

Results and discussions

In the paper by Qin [36], the attenuation coefficient for a 1MHz ultrasound is given by 0.23 dB/mm. For our pipe dimension of 20 mm, the maximum attenuation for a wave traveling through and back is 0.23×20×2 = 9.2 dB, which corresponds to a reduced amplitude of signal by a factor of 2.88. This is, however, not ideal to implement in Abaqus. Instead, we plan to use the Prony series material property (viscoelastic modeling) in Abaqus with suitable fictional relaxation modulus ratio and suitable fictional relaxation time to represent the attenuation. Our preliminary study shows that the Prony series viscoelastic model can represent the attenuation when suitably calibrated. We are continuing to work on the appropriate viscoelastic modeling for HDPE.

A comparison between purely elastic and viscoelastic properties is shown in Figure 7, and it shows that we can use the Prony series with a reasonable relaxation time to represent the attenuation effect. By tuning this characteristic time coefficient, we can acquire different degrees of attenuation. This suggests that we need to use experiments to calibrate this coefficient.

Table 1. Material properties for HDPE.

Elastic properties			**Viscoelastic properties**	
Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Relaxation modulus ratio	Relaxation time (s)
954	0.97	0.43	0.5	10^{-7}

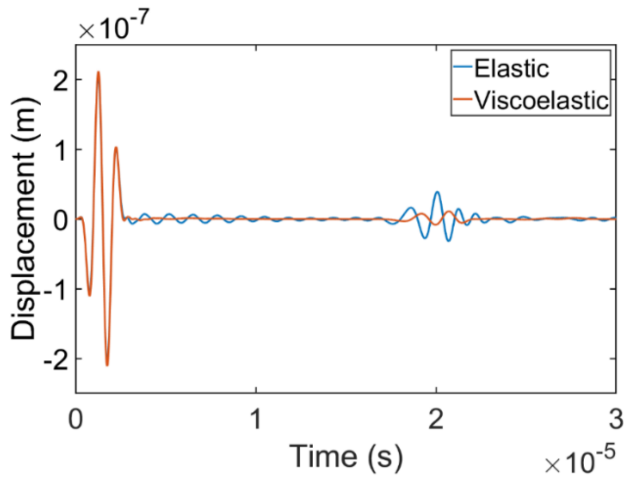

Figure 7. Comparison of reflected signal for elastic and viscoelastic properties.

Overall future goals

Task 1: We will conduct preliminary experiments to test how environmental factors impact the SCG of HDPE specimens in the upcoming quarters. These preliminary experiments will utilize our in-house long-term creep test setup, thermal and chemical exposure chamber. Additionally, imaging studies of the fracture surface will be performed as well following the preliminary mechanical experiment. Experimental data will help us conduct mechanistic modeling and develop physics-based models to evaluate the fitness of service for HDPE pipelines. We will study published experimental data and use our experimental data to assess models.

Task 2: In the upcoming quarters, we will establish a machine learning algorithm for the crack characterization inside HDPE pipes. Databases will be generated using batch job submission in Abaqus. Experiments will be carried out to calibrate the attenuation effect of ultrasound propagation inside HDPE.

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