Influence of Wall Thickness on the Thermo-Mechanical Properties of Aging HDPE pipes under Freeze-thaw cycles in Quebec Province, Canada

Khanh Q. Nguyen, Patrice Cousin, Khaled Mohamed, Mathieu Robert and Brahim Benmokrane

November 6, 2021

CSCE 2021 Annual Conference

Inspired by Nature – Inspiré par la Nature

26-29 May 2021

INFLUENCE OF WALL THICKNESS ON THE THERMO-MECHANICAL PROPERTIES OF AGING HDPE PIPES UNDER FREEZE-THAW CYCLES IN QUEBEC PROVINCE, CANADA

Khanh Q. Nguyen[1,2,*], Patrice Cousin[1], Khaled Mohamed[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: The present study addresses the question of what effect wall thickness would have on the thermo-mechanical properties of corrugated HDPE pipes aging under freeze-thaw cycles in Quebec province, from the surface to its interior. Five commercial corrugated HDPE pipes for transportation infrastructure applications aging within 14 years from different locations in Quebec province (Canada) were examined. The impact of wall thickness (4.50, 7.00, 7.80, 8.90, and 10.40 mm) on decomposition, thermal properties, and long-term modulus of pipes was reported by thermal analysis techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), and Dynamic Mechanical Analysis (DMA). The antioxidant depletion at the exterior and interior walls of pipes was investigated by oxidation induction time (OIT) measurements. The results indicate that all investigated pipes meet a minimum 20-minute OIT requirement where the antioxidant content is sufficient to withstand oxidation. The antioxidants extraction process occurred through the wall thickness which explains the significant difference in the thermal properties of pipes at the exterior and interior walls. However, the change of long-term modulus to variable wall thickness is relatively small.

Keywords: High-density polyethylene (HDPE) aging pipes; thermal and mechanical properties; thermal analysis techniques; antioxidant extraction; wall thickness; freeze-thaw cycles; transportation infrastructure applications.

1 INTRODUCTION

HDPE pipe has become one of the most widely used thermoplastic materials for underground structures such as drainage, sewer due to its good properties. The advantage of using corrugated HDPE pipes, such as its low maintenance cost, excellent corrosion resistance, flexibility, and hydraulic efficiency (PPI Handbook 2008, Petroff 2013, Rubeiz 2004, Nguyen et al. 2021), has increased its tendency to contribute to transportation infrastructure applications with the underground structure compared to metal and concrete pipes. Previous works have determined the impact of material properties, wall geometry of corrugated HDPE pipes on the pipe's service lifetime (Watkins et al. 1987, Moser 1998, Hsuan and McGrath 1999). However, there is little understanding of pipe wall thickness's impact on the life expectancy of pipes. All pipe manufacturers have determined the minimum thickness as well as the diameter of the pipe (nominal diameter and thickness) to meet performance. However, a controversial question that remains unclear is how the effect of wall thickness variation would have on their thermo-mechanical properties. In general, a thicker walled pipe increases resistance to rapid crack propagation, corrosion resistance, and fatigue mechanisms for pipes rather than a thinner wall. The pipe wall thickness also affects the permeability rate when a pipe works under conditions in contact with liquid solutions (PPI Handbook 2008). Moreover, ultraviolet light is one of the factors causing major oxidation differences through the thickness at the surface and internal of the material. (Rowe et al. 2014) have reported that antioxidants depletion faster from thinner HDPE geomembrane thickness. Results of crystallinity, melt index, and stress-crack resistance tests in (Rowe et al. 2010) also concluded that the degradation rate of thinner HDPE geomembrane was the fastest. Sharing the same point of view, (Cai et al. 2014) also showed that there was a significant change in the mechanical properties of rubber's thickness, from the surface to its interior. Thicker rubber products had a longer aging time rather than thinner products.

For pressure systems, the wall thickness significantly affects the mechanical properties of the PE pipe. (Liu et al. 2018) studied the effect of pipe wall thickness on the mechanical response. The results showed an increase in wall thickness can decrease the pipe stress. PE pipes with thicker walls were more capable of withstanding internal pressure. (Krishnaswamy 2007) concluded that pipe wall thickness was not significantly affected the brittle failure of pipelines under internal pressure. However, for ductile failure, a thinner wall thickness was easily observable through creep rupture tests.

For non-pressure systems, a limited amount of researcher is found in the literature to discuss the influence of wall thickness on the thermo-mechanical properties of aging pipes, especially under freeze-thaw cycles. In the present study, five aging HDPE pipes for transportation infrastructure applications (non-pressure) were examined. This study aims to investigate and determine pipe wall thickness impact on thermal properties and long-term modulus of pipes by thermal analysis techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), and Dynamic Mechanical Analysis (DMA).

2 MATERIALS AND METHODS

2.1 Materials

Five commercial corrugated HDPE pipes manufactured with virgin resin and additives aging within 14 years at five different locations in Quebec province are examined. Their service conditions are similar. These pipes work in a typical Quebec environment, where freeze-thaw cycles often occur. The present study focuses on the climate impact of Canada's winter period (e.g., low temperature, temperature variations between day and night, and freeze-thaw cycles) on material properties. From the historical weather record in Quebec, the average highest and lowest temperatures per year are 40^{0}C and -40^{0}C, respectively. Weather characteristics with long, cold winters and short summers are among the factors that affect the long-term performance of pipelines. Moreover, this cold condition has been one of the causes that can make some plastic drainage products brittle. The research included five pipes P1, P2, P3, P4, and P5 with the same nominal diameter of 900 mm, and the nominal wall thickness of 4.50, 7.00, 7.80, 8.90, and 10.40 mm, respectively. To conduct the investigation, specimens were cut from the corrugated portion of the large pipe (figure 1a). Tests are conducted from the external and internal parts of specimens as illustrated in figure 1b.

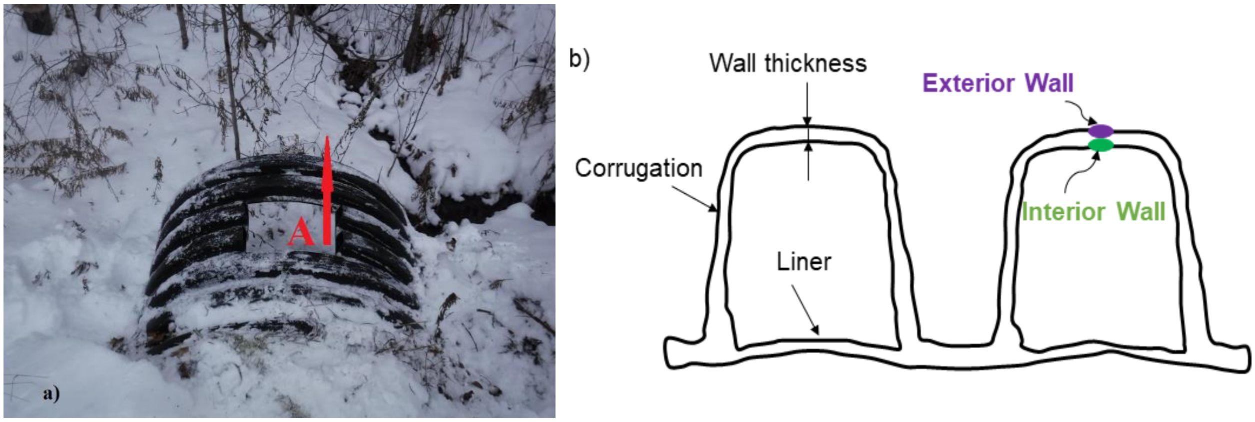

Figure 1: a) Investigated HDPE pipes b) Longitudinal section A of pipes

2.2 Test methods

In order to evaluate wall thickness impact on decomposition, thermal properties, and long-term modulus, tests were conducted using thermal analysis techniques such as FTIR, DSC, and DMA.

2.2.1 Fourier transform infrared spectroscopy (FTIR)

The chemical modification and structural analysis were performed by the FT/IR-4600 spectrometer equipped with a TGS detector. A rectangular specimen (15 mm x 15 mm) was analyzed over the 4000-600 cm^{-1} wavenumber range at 4 cm^{-1} resolution.

2.2.2 Differential scanning calorimetric (DSC)

In order to assess the antioxidant consumption at the exterior and interior wall of pipes, oxidative induction time (OIT) was measured by DSC 6000 from Perkin-Elmer in accordance with (ASTM D3895 2014) standard. A 5-10 mg specimen was heated from room temperature to 200^0C at a rate of 30^0C/min under nitrogen. The specimen was maintained at 200^0C with an isothermal step, while the gas was changed by oxygen. The OIT value obtained when an exothermic peak was detected.

2.2.3 Dynamic mechanical analysis (DMA)

Time-temperature superposition (TTS) is an accelerated test used to evaluate the viscoelastic behavior and long-term modulus of polymers. The measurements were carried out by DMA 8000 from Perkin-Elmer, built-in with the TTS method. A single cantilever model was used with the distance between 2 clamps was 17.5 mm. A rectangular specimen of 2-4 mm in thickness, 3-8 mm in width, and 30-40 mm in length was analyzed over the 5-100^0C temperature range, along with 0.01Hz-100Hz frequencies.

3 RESULTS AND DISCUSSIONS

3.1 FTIR Analysis

The results of FTIR analysis of five specimens with exterior and interior walls are shown in figure 2 (a, b, c, d, and e). Polyhydroxyl stretch is observed at 3345 cm^{-1} in the spectra of HDPE pipes. The peaks at 2913 and 2847 cm^{-1} demonstrate typical bands of C–H groups of the HDPE. These peaks are assigned to asymmetric and symmetric stretching vibrations of C–H groups. It is easy to observe that the presence of ketonic carbonyl groups caused by oxidation at 1646 cm^{-1} (Luongo 1960). It can be seen from figure 2 that the intensity absorption of peak 1646 cm^{-1} at the exterior wall is higher than the interior wall. A possible explanation for this phenomenon is the formation of esters caused by oxidation (Luongo 1960). The presence of CH_2 bending is observed at 1465 cm^{-1} (Khan et al. 2016). Moreover, the peak at 1025 cm^{-1} is assigned to a composite of the C–OH and C–O–C groups formed upon oxidation (Luongo 1960). Finally, there is the presence of CH_2 rocking at 722 cm^{-1} (Gulmine et al. 2002).

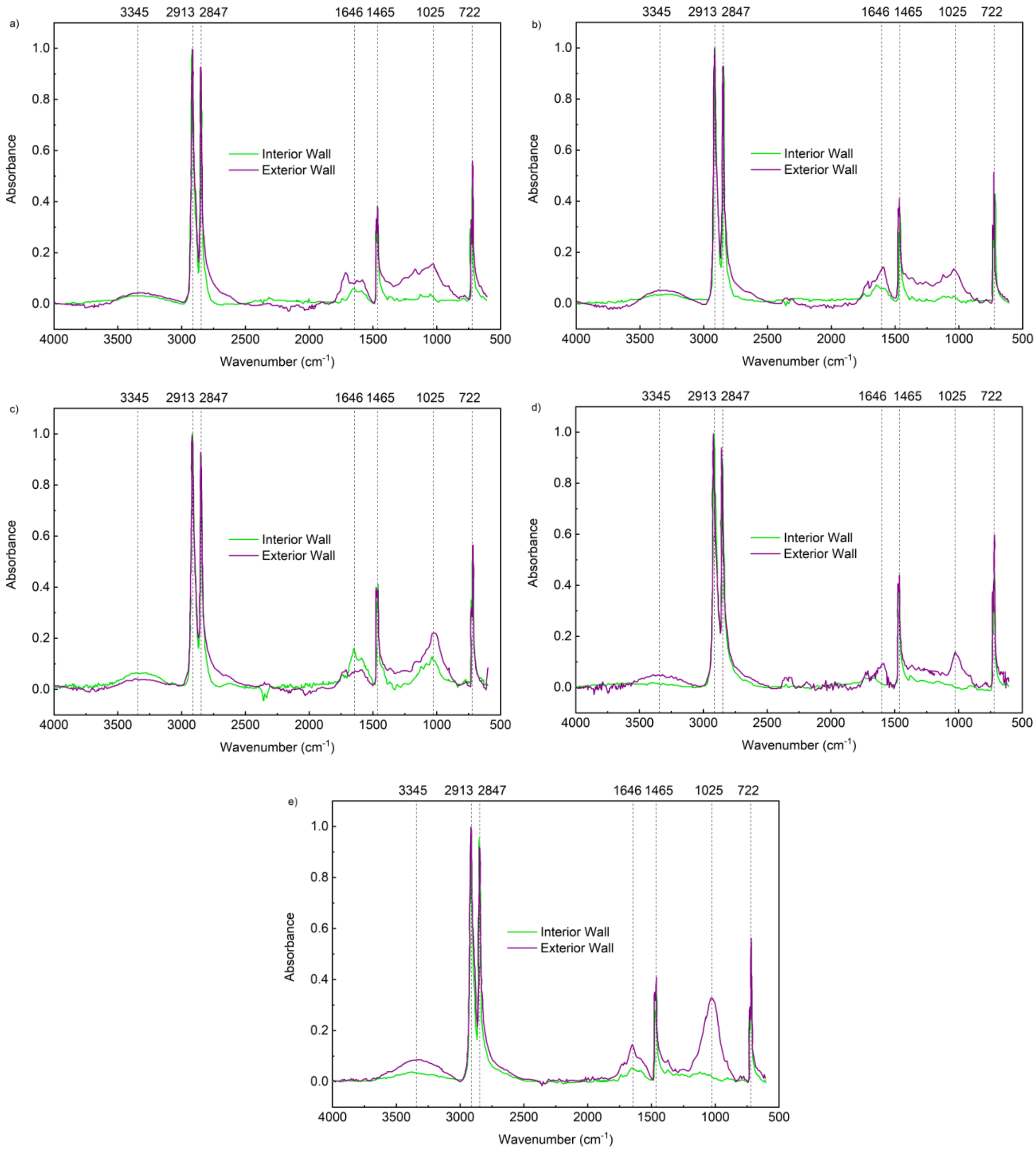

Figure 2: FTIR spectrum of HDPE pipes a) P1 b) P2 c) P3 d) P4 e) P5

The difference between the intensity absorption of peaks in the spectra at the exterior and interior walls is observed relatively clearly. Specifically, it is most clearly observed at 1025 cm^{-1} in P5 pipe with a thicker wall thickness of 10.40 mm compared to other pipes. The better oxidation takes place at the exterior wall.

It should be noted that the freeze-thaw cycles and ultraviolet light, which can facilitate the extraction of antioxidants at this position through wall thickness rather than the interior wall.

3.2 Oxidation induction time (OIT)

Oxidation induction time (OIT) is a measurement in which evaluates the amounts of antioxidants present in a pipe. In other words, a higher OIT value demonstrates a greater antioxidant contained in a pipe. The current (AASHTO M294 2018) standard ''*Specification for Corrugated Polyethylene Pipe, 300- to 1500-mm (12- to 60-in.) Diameter*'' does not require a minimum OIT value. However, a 20-minute OIT requirement when tested to (ASTM D3895 2014, Pluimer et al. 2018) is recommended. Table 1 shows the OIT values at the exterior and interior walls of five HDPE pipes. All pipes meet a minimum 20-minute OIT requirement. The variation of OIT value between pipes is explained by the antioxidant package and content. However, these pieces of information are rarely disclosed as the manufacturer's secrets. The results show that thinner pipe wall thickness (P1), OIT values on the exterior and interior walls have no difference. For P2, P3, P4 pipes, this difference is clearly indicated. However, with a thicker pipe wall thickness (P5), this difference is not so obvious. In fact, antioxidant depletion in the exterior and interior walls is highly dependent on the antioxidants present in the pipe, wall thickness, and working conditions of each pipe in different regions.

Table 1: OIT value at the exterior and interior walls of HDPE pipes

OIT (min)	**P1**	**P2**	**P3**	**P4**	**P5**
Exterior wall	22	46	22	40	32
Interior wall	25	76	96	77	46
Wall thickness (mm)	4.50	7.00	7.80	8.90	10.40

3.3 Long-term modulus

The TTS method allows the DMA data can be applied to the measuring range of the DMA 8000 device (0.001 Hz to 600 Hz), and the modeling behavior of the material at much higher or lower frequencies. In that case, a high frequency can be likened to a short time and a low temperature; and a low frequency at a long time and high temperature since low frequencies allow better relaxation of the polymer. In the present study, a rectangular specimen was used. The strain of this test was 0.05%. The temperature range was from 5 to 100^{0}C, in steps of 5^{0}C with the frequency range of 0.01 Hz to 100 Hz (figure 3a). The testing time was 10 hours.

The effects of temperature and frequency variations are interchangeable according to the TTS principle. Therefore, data obtained over a limited frequency range can be extended by applying a shift factor on data obtained over a range of temperatures. These curves are shifted to generate a master curve describing the behavior of HDPE by choosing a reference temperature. Temperatures below the reference temperature are shifted to higher frequencies, and temperatures above are shifted to lower frequencies. In the present study, a reference temperature of 50^{0}C (softening temperature) was used to generate a single master curve (figure 3b) using the WLF (Williams-Landel-Ferry) equation 1.

[1] $$\mathrm{Log}(a_T) = \frac{-C_1\,(T-T_r)}{C_2 + T-T_r}$$

Where, a_T is the frequency shift factor, C_1 and C_2 are the WLF coefficients, T is the temperature, and T_r is the reference temperature. C_1 and C_2 are determined from the experimental data and are dependent on reference temperature. In this study, the values for C_1 and C_2 are found to be 30 K and 265 K, respectively.

The long-term modulus values of the pipes are shown in table 2. Results indicated that there is no significant difference in the long-term modulus value between thinner and thicker pipe wall thickness. It should be noted that the limitations of the TTS DMA method are a relatively small test specimen, a variability of specimen size at different tests also affects the test results. However, the test duration of this method is relatively short within 10 hours.

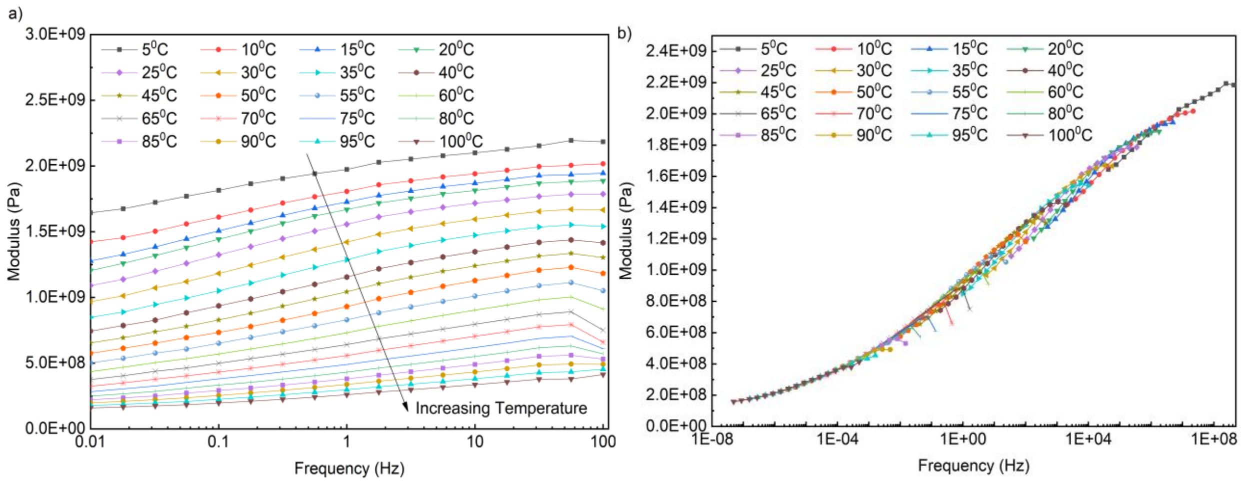

Figure 3: A typical lot of a) temperature-frequency sweep b) master curve for P3 pipe

Table 2: Long-term modulus value of HDPE pipes

	P1	P2	P3	P4	P5
Long-term modulus (MPa)	230	223	214	189	207
Wall thickness (mm)	4.50	7.00	7.80	8.90	10.40

4 CONCLUSION

In this study, the wall thickness impact on thermo-mechanical properties of aging HDPE pipes under freeze-thaw cycles in Quebec is evaluated. The following conclusions are the finding of the present study:

- For aging HDPE pipes under freeze-thaw cycles in Quebec province, in addition to typical bands of C–H, CH_2 at 2913, 2847, 1465, and 722 cm^{-1}, FTIR spectra also show some peaks at 3345, 1646, and 1025 cm^{-1} caused by oxidation. The intensity absorption of peaks in the spectra at the exterior and interior walls is different.
- All investigated pipes meet a minimum 20-minute OIT requirement where the antioxidant content is sufficient to withstand oxidation by sunlight. Antioxidant depletion in the exterior and interior walls is highly dependent on the antioxidant package and content present in the pipe, pipe wall thickness, and working conditions of each pipe. It should be noted, however, that the antioxidant packages are rarely disclosed as the manufacturer's secrets and therefore not available for the authors.
- The freeze-thaw cycles and ultraviolet light can be the causes that facilitate antioxidant extraction through the wall thickness.
- It is interesting to note that the long-term modulus of pipes is not significantly affected by wall thickness.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

This study was conducted with financial support from the Natural Science and Engineering Research Council of Canada (NSERC), the NSERC Research Chair in Innovative FRP Reinforcement for Sustainable Concrete Infrastructures, the Tier-1 Canada Research Chair in Composite Materials for Civil structures, the Fonds Québécois de la recherche sur la nature et les technologies (FQRNT), the Ministry of Transportation of Quebec (MTQ), and the University of Sherbrooke Research Centre on Composite Materials (CRUSMaC).

References

ASTM D3895. 2014. “Standard Test Method for Oxidative-Induction Time of Polyolefins by Differential Scanning Calorimetry.” https://www.astm.org/Standards/D3895.htm.

Cai, Yi Kun, Xiao Bing Ma, Hao Wang, and Yu Zhao. 2014. “Impact of Thickness on Rubber Aging Life.” *Advanced Materials Research* 1035 (October): 122–27. https://doi.org/10.4028/www.scientific.net/AMR.1035.122.

Gulmine, J.V, P.R Janissek, H.M Heise, and L Akcelrud. 2002. “Polyethylene Characterization by FTIR.” *Polymer Testing* 21 (5): 557–63. https://doi.org/10.1016/S0142-9418(01)00124-6.

Hsuan, Yick Grace, and Timothy J McGrath. 1999. HDPE Pipe: Recommended Material Specifications and Design Requirements. Vol. 429. *Transportation Research Board*.

Khan, Shahzad Maqsood, Nafisa Gull, Muhammad Azeem Munawar, Atif Islam, Saba Zia, Muhammad Shafiq, Aneela Sabir, et al. 2016. “2D Carbon Fiber Reinforced High Density Polyethylene Multi-Layered Laminated Composite Panels: Structural, Mechanical, Thermal, and Morphological Profile.” *Journal of Materials Science & Technology* 32 (10): 1077–82. https://doi.org/10.1016/j.jmst.2016.06.011.

Krishnaswamy, Rajendra K. 2007. “Influence of Wall Thickness on the Creep Rupture Performance of Polyethylene Pipe.” *Polymer Engineering & Science* 47 (4): 516–21. https://doi.org/10.1002/pen.20729.

Liu, Xiaoben, Hong Zhang, Mengying Xia, Kai Wu, Yanfei Chen, Qian Zheng, and Jun Li. 2018. “Mechanical Response of Buried Polyethylene Pipelines under Excavation Load during Pavement Construction.” *Engineering Failure Analysis* 90 (August): 355–70. https://doi.org/10.1016/j.engfailanal.2018.03.027.

Luongo, J. P. 1960. “Infrared Study of Oxygenated Groups Formed in Polyethylene during Oxidation.” *Journal of Polymer Science* 42 (139): 139–50. https://doi.org/10.1002/pol.1960.1204213916.

M 294, AASHTO. 2018. Standard Specification for Corrugated Polyethylene Pipe, 300- to 1500-Mm (12- to 60-in.) Diameter. American Association of State Highway and Transportation Officials.

Moser, A. P. 1998. “Structural Performance of Buried Profile-Wall High-Density Polyethylene Pipe and Influence of Pipe Wall Geometry.” *Transportation Research Record: Journal of the Transportation Research Board* 1624 (1): 206–13. https://doi.org/10.3141/1624-24.

Nguyen K. Q., C. Mwiseneza, K. Mohamed, P. Cousin, M. Robert, and B. Benmokrane. 2021. “Long-Term Testing Methods for HDPE Pipe - Advantages and Disadvantages: A Review.” *Engineering Fracture Mechanics*. doi: 10.1016/j.engfracmech.2021.107629

Petroff, Larry J. 2013. “Occasional and Recurring Surge Design Considerations for HDPE Pipe.” In *Pipelines 2013*, 161–70. Fort Worth, Texas, United States: American Society of Civil Engineers. https://doi.org/10.1061/9780784413012.014.

Pluimer, Michael, Joel Sprague, Richard Thomas, Leslie McCarthy, Andrea Welker, Shad Sargand, Ehab Shaheen, and Kevin White. 2018. Field Performance of Corrugated Pipe Manufactured with Recycled Polyethylene Content.

PPI Handbook, Plastics pipe institute. 2008. “Chapter 3 - Material Properties,” 61.

Rowe, R. Kerry, Fady B. Abdelaal, and M. Zahirul Islam. 2014. “Aging of High-Density Polyethylene Geomembranes of Three Different Thicknesses.” *Journal of Geotechnical and Geoenvironmental Engineering* 140 (5): 04014005. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001090.

Rowe, R. Kerry, M. Z. Islam, and Y. G. Hsuan. 2010. “Effects of Thickness on the Aging of HDPE Geomembranes.” *Journal of Geotechnical and Geoenvironmental Engineering* 136 (2): 299–309. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000207.

Rubeiz, Camille George. 2004. “Case Studies on the Use of HDPE Pipe for Municipal and Industrial Projects in North America.” In *Pipeline Engineering and Construction*, 1–10. San Diego, California, United States: American Society of Civil Engineers. https://doi.org/10.1061/40745(146)22.

Watkins, R. K., J. M. Dwiggins, and W. E. Altermatt. 1987. “Structural Design of Buried Corrugated Polyethylene Pipes.” *Transportation Research Record* 1129: 12–20.