Degradation of PE pipes for the conveyance of drinking water and lifetime prediction

Mechanics of mAterials for enGineering and Integrity of Structures - MAGIS Paris

2024-2025

Achraf Benmalk

achraf.benmalk@ensam.eu

Le 17/01/2025

Reviewer:
Supervisors: Xavier COLIN Juan Pablo MARQUEZ COSTA
Laboratoire Procédés et Ingénierie en Mécanique et Matériaux (PIMM) 51 Boulevard de l'Hôpital – 75013, Paris, France

1. Motivation

High-Density Polyethylene (HDPE) has been the predominant material for drinking water distribution networks since the 1990s due to its unique properties, including corrosion resistance, flexibility, light weight, toughness, easy installation, water neutrality, and leak tightness (Plastics Pipe Institute, 2008). The newest generation of HDPE, PE100-RC, is estimated to have a service lifetime of up to 100 years under conditions of internal overpressure with pure distilled water. However, the use of trenchless installation techniques and coarse-grained backfill materials introduces the risk of localized inhomogeneous stress fields caused by rocks pressing onto the pipe's outer wall (Lenz, 2001). This point loading can significantly reduce the service life of buried pipes, leading to premature failure.

Microscopic analyses have revealed that cracks caused by point loading appear on the internal surface of polymer conduits (Dossier technique conduit 9010 RC en PE 100-RC). This raises the question of whether the observed damage results solely from the mechanical effect of punching or if there is a complex interaction between punching and the chemical degradation induced by chlorinated disinfectants commonly used in drinking water treatment.

Ensuring the reliability of drinking water distribution networks is crucial for public health and the proper functioning of urban infrastructure. Large investments are made annually in repairing and extending these networks. This study aims to investigate the specific effect of puncturing on the structural properties of polymer pipes used in drinking water systems, determining the extent to which internal deformations affect lifetime and performance, and assessing their potential to lead to system failures. It will explore whether the observed damage is influenced by factors such as chemical degradation in addition to puncturing. Understanding the combined impact of these factors is essential for comprehending the degradation mechanisms and developing prevention and improvement strategies.

In the first part of this project, a comprehensive analysis was conducted to investigate the performance and lifetime of PE100 pipes under the combined effects of mechanical punching and chemical degradation. Computational modeling using Abaqus Finite Element software was employed to simulate the mechanical stresses and strains in PE100 pipes under various conditions, including pipe geometry, punch dimensions, indentation depth, loading, internal pressure, and thermal loads. The study revealed the importance of considering temperature-dependent material properties, such as Young's modulus and the coefficient of thermal expansion, for accurate predictions of pipe deformation and stress distribution. Additionally, the effect of different hardening models on the elasto-plastic behavior of PE100 pipes was investigated, highlighting the need for realistic material models to capture the complex stress-strain response under combined loading conditions.

Building upon the findings of the first part, this bibliographic report aims to provide a comprehensive overview of the current state of research on the degradation mechanisms and lifetime prediction of PE pipes in drinking water distribution networks, with a specific focus on the combined effects of mechanical stress from point loading and chemical degradation due to chlorinated disinfectants. By integrating computational modeling and experimental chemical degradation assessment, this research seeks to provide valuable insights into the long-term performance and durability of PE pipes in drinking water distribution networks.

Although experimental tests accounting for point load effects is rare due to their complexity and duration, this study focuses on the numerical prediction of point load effects over pipe life and their

coupling with oxidative degradation initiated by attack from disinfectants. The findings and recommendations presented in this report will inform the development of strategies for the prevention, improvement, and maintenance of PE pipes, ultimately contributing to the safe and efficient operation of drinking water distribution networks.

2. Bibliography

2.1 Chemical Degradation Mechanisms in PE Pipes

The chemical degradation of PE pipes exposed to chlorine dioxide (ClO_2) during water disinfection has been extensively investigated, focusing on oxidative degradation, molecular weight reduction, antioxidant depletion, and embrittlement (Colin et al., 2009). Colin et al. identified a critical molecular weight ($M_w^{critical} \approx 70, kg/mol$) below which PE becomes brittle and highlighted the role of hydroperoxide accumulation in triggering chain scission when their concentration surpasses a critical threshold (Figure 1) (Colin et al., 2009). The reduction in molecular weight due to chain scission was quantified using the Saito relationship:

$$\frac{1}{M_w} - \frac{1}{M_{w0}} = \frac{s}{2} - 2x \quad \text{(Eq. 1)}$$

$$\frac{1}{M_n} - \frac{1}{M_{n0}} = s - x \quad \text{(Eq. 2)}$$

Where:

- (M_w, M_n): Weight and number average molar mass after degradation

- (M_{w0}, M_{n0}): Initial weight and number average molar mass

- (s): Number of chain scissions

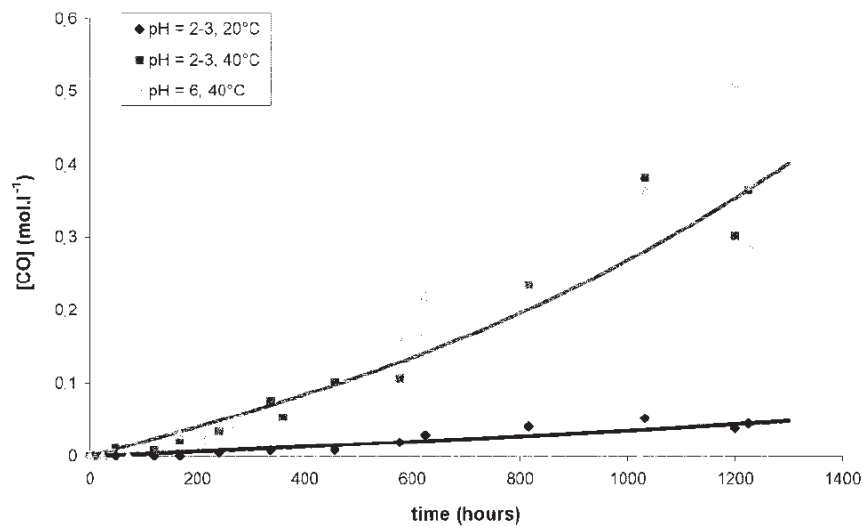- (x): Number of crosslink events

FIG. 1. Kinetic curves of carbonyl build-up of PE films after immersion in chlorine dioxide (Colin et al., 2009)

The study also revealed the surface-limited nature of the degradation, with oxidation and chlorine incorporation concentrated near the pipe surface, forming a brittle layer (Figure 2) (Colin et al., 2009). A predictive kinetic model was developed to simulate oxidation kinetics and embrittlement progression, aligning well with experimental data. These findings highlight the importance of antioxidant-stabilized PE materials in chlorine dioxide-treated water systems and the need for kinetic degradation models to improve service life predictions and maintenance planning (Colin et al., 2009).
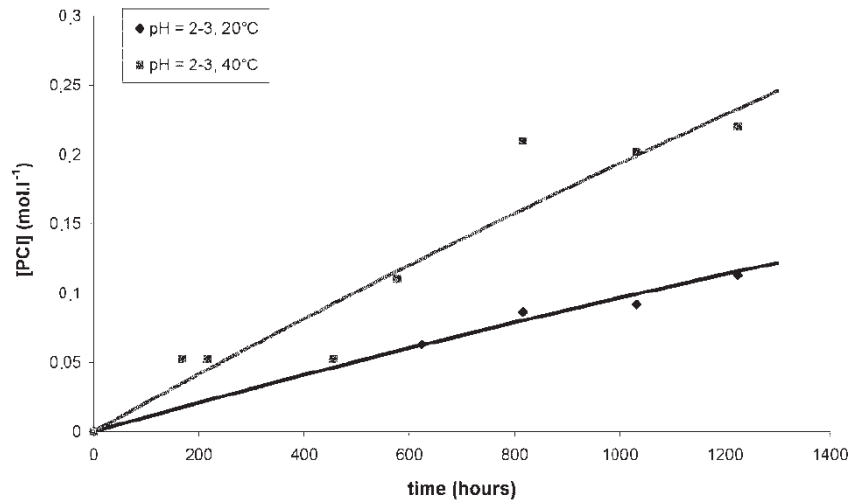

FIG. 2. Kinetic curves of weight average molar mass of PE films after immersion in chlorine dioxide (Colin et al., 2009)

Yu et al. investigated the deterioration mechanisms of polyethylene pipes exposed to water containing chlorine dioxide, providing insights into the degradation-assisted crack propagation phenomenon in PE pipes (Yu et al., 2011). The study revealed that chlorine dioxide causes aggressive attack near the inner wall surface through a single electron transfer process, with the chemical consumption of antioxidants being approximately four times faster compared to chlorinated water, following the reaction kinetics:

$$\frac{\partial [AO]}{\partial t} = -k[AO][ClO_2] \quad (Eq.\,3)$$

Where:

- $([AO])$: Antioxidant concentration

- $([ClO_2])$: Chlorine dioxide concentration

- (k): Reaction rate constant

The research identified a critical "degradation-assisted crack propagation" mechanism, where cracks form during hydrostatic pressure testing but cease propagation upon reaching non-degraded material. However, continued chemical attack near the crack tip enables further crack growth (Figure 3) (Yu et al., 2011). The study also quantified the relationship between oxidation depth and exposure time using the following equation:

$$x = \sqrt{2Dt} \quad (Eq.\,4)$$

Where:

- (x): Oxidation depth

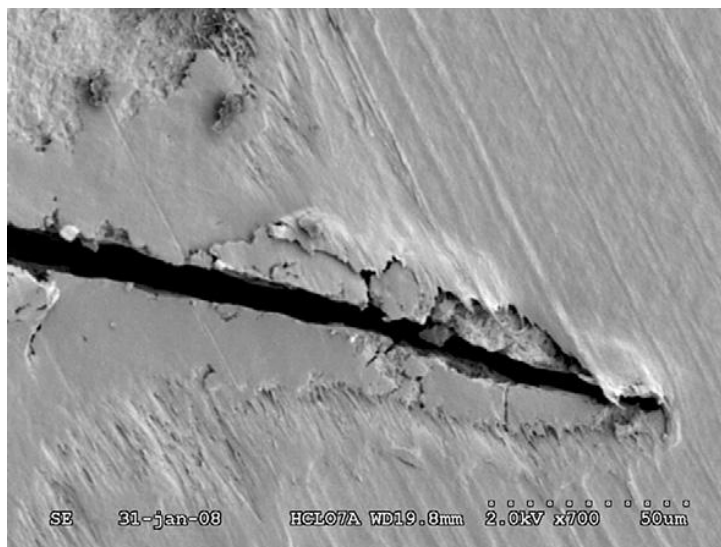- (D): Diffusion coefficient

- (t): Exposure time

FIG. 3. Scanning electron micrograph showing crack propagation pattern in PE pipe after 121h exposure to water containing 4ppm chlorine dioxide (Yu et al., 2011).

The findings demonstrate how this mechanism can cause premature fractures even in thick-walled pipes when only the surface is affected by degradation, emphasizing the importance of understanding this coupled degradation mechanism for accurate lifetime prediction of PE pipes in chlorinated water systems (Yu et al., 2011).

2.2 Property Evolution During Chemical Attack

The effects of chlorinated water exposure on the mechanical and chemical integrity of polyethylene pipes have been extensively studied, focusing on antioxidant depletion, molecular weight reduction, and mechanical property degradation [6-9]. Dear and Mason investigated medium-density polyethylene (MDPE) pipes exposed to varying chlorine concentrations $(0-120,000\,mg/L)$ at elevated temperatures $(60°C-80°C)$ (Dear & Mason, 2006). Tensile testing revealed a decrease in yield stress and elongation at break with prolonged chlorine exposure, increasing the risk of brittle failure. Oxidation induction time (OIT) measurements showed significant antioxidant loss, especially near the pipe's inner surface, leading to surface oxidation (Figure 4) (Dear & Mason, 2006). The OIT decay with time was modeled using the following equation:

$$OIT(t) = OIT_0 \cdot e^{-kt} \quad (Eq.\,5)$$

Where:

- (OIT_0): Initial oxidation induction time

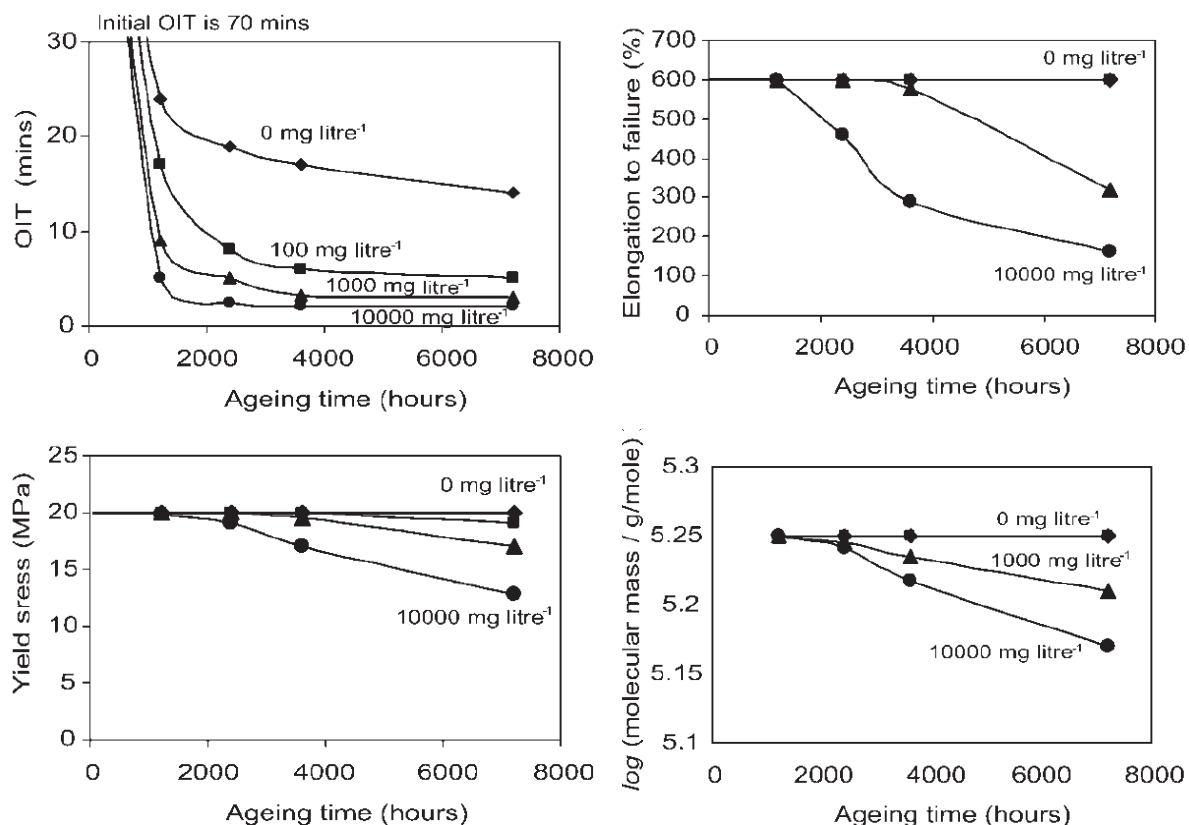- (k): Rate constant for antioxidant depletion

FIG. 4. Oxidation induction time (OIT) recorded at 190 °C for samples taken from pipes tested at 95 °C for different periods of time with internal chlorinated (3 ppm) water as a function of the distance from the inner wall (Dear & Mason, 2006).

Gel Permeation Chromatography (GPC) analysis revealed a noticeable drop in molecular weight due to chain scission at high chlorine concentrations, weakening the polymer (Figure 5) (Dear & Mason, 2006). Chlorine penetration created a degraded surface layer, with degradation mainly confined to the first few millimeters. Brittle failure modes dominated under combined chemical and mechanical stress, especially at higher chlorine levels and hoop stresses, calculated using the following equation:

$$\sigma_{hoop} = \frac{p_{int} \cdot (d - 2s)}{2s} \quad (Eq.6)$$

Where:

- (p_{int}): Internal pressure

- (d): Outer diameter
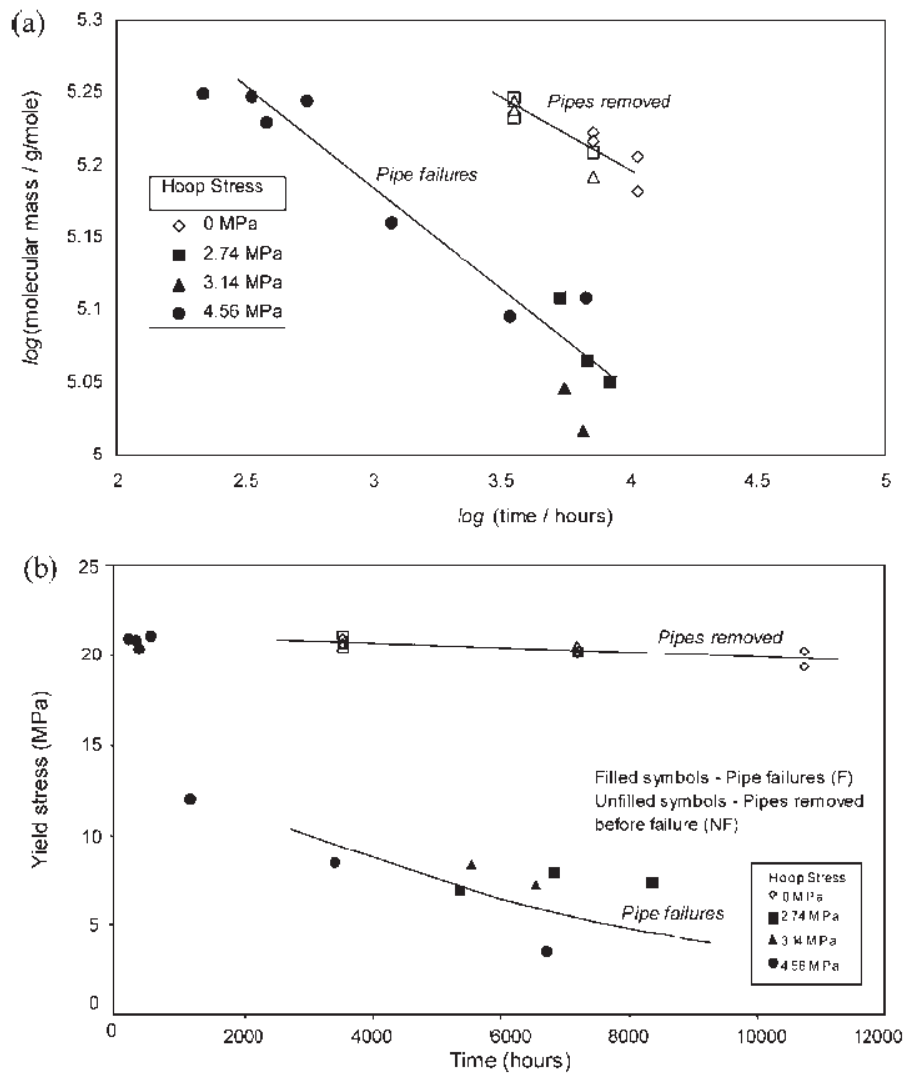
- (s): Wall thickness

FIG. 5. Molar mass distribution of a sample taken from the layer of porous material from a pipe exposed to 105 °C chlorinated (3 ppm) water for 438 h. (Dear & Mason, 2006).

These studies provide critical insights into how chlorine accelerates oxidative degradation and mechanical weakening of PE pipes, emphasizing the need for robust antioxidant systems to mitigate chlorine-induced degradation [6-9]. The findings highlight the increased likelihood of brittle failure due to chemical degradation, informing pipe design and maintenance strategies. Recommendations include enhancing antioxidant formulations, implementing regular OIT monitoring, and considering surface treatments to reduce chlorine diffusion into the pipe material (Dear & Mason, 2006).

Zheng et al. examined the mechanical behavior of notched high-density polyethylene (HDPE) pipes, analyzing how various notch geometries affect fatigue, creep, and ultimate load capacity (Zheng et al., 2019). The study introduced a novel notched HDPE ring (NHR) specimen methodology and compared results with conventional notched HDPE pipe (NHP) specimens using finite element modeling (FEM) predictions. The normalized ultimate load was described using the equation:

$$\frac{P_{\text{notched}}}{P_{\text{virgin}}} = 1 - k \left(\frac{h_g}{H}\right)^n \quad (Eq.\,7)$$

Where:

- (P_{notched}): Ultimate load of notched specimen

- (P_{virgin}): Ultimate load of virgin specimen

- (h_g): Groove depth

- (H): Wall thickness

- $(k), (n)$: Empirical constants

The study revealed that U-type and V-type grooves caused more significant decreases in burst pressure compared to L-type notches. The authors validated their FEM simulations against experimental data (Figure 6), providing a reliable framework for predicting mechanical responses of notched PE pipes (Zheng et al., 2019).
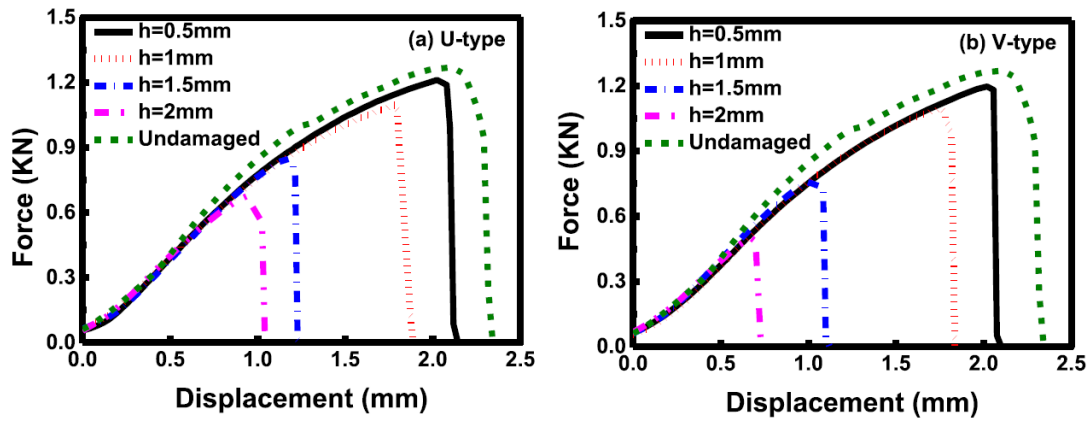

FIG. 6. Load-displacement curves for NHR specimens with different notch types showing reduced load capacity with increased notch depth. (Zheng et al., 2019).
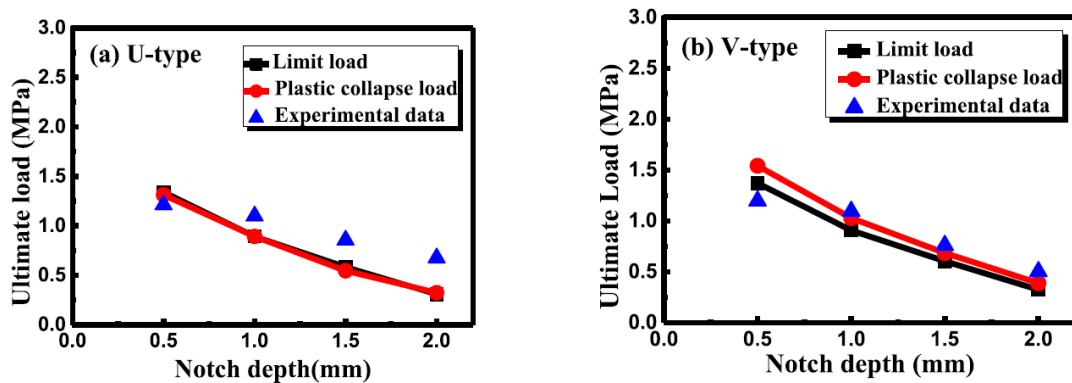

FIG. 7. Comparison of experimental and FEM-predicted burst pressures for various notch geometries (Zheng et al., 2019).

Fayolle et al. explored the mechanisms leading to the embrittlement of polyethylene (PE) due to thermal oxidation, providing a detailed analysis of how chain scission in the amorphous regions of PE causes a reduction in mechanical performance, culminating in brittle failure (Fayolle et al., 2007). The study exposed PE films to air at 80°C and 90°C to simulate long-term oxidative degradation and assessed changes in elongation at break and yield stress during degradation using tensile testing. Infrared spectroscopy (IR) was employed to detect oxidation products, particularly carbonyl group formation, while rheological measurements were used to assess changes in molecular weight distribution due to chain scission. The research identified a critical molar mass threshold ($M_w^{critical} \approx 90, kg/mol$) below which PE transitions from ductile to brittle behavior (Figure 8) (Fayolle et al., 2007).
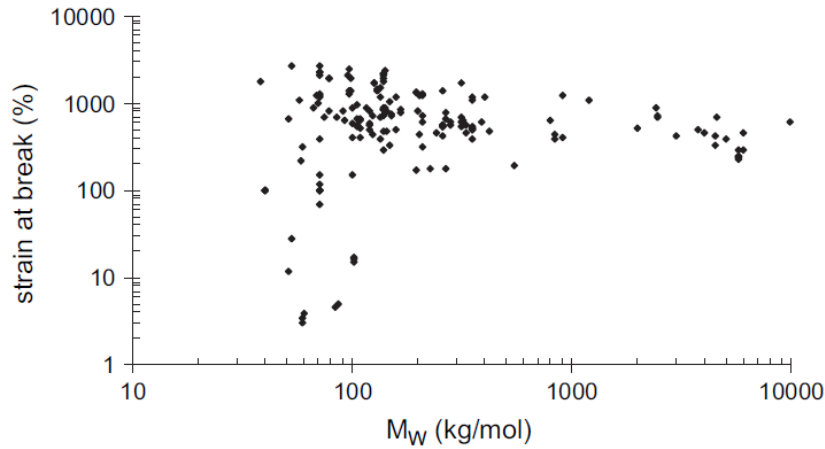

FIG. 8. Strain at break as a function of weight average molar mass (Fayolle et al., 2007).

The study revealed that thermal oxidation primarily causes random chain scission in the amorphous phase, leading to mechanical property degradation. The relationship between chain scission and crosslinking was quantified using the saito equations $(Eq. 1)(Eq. 2)$

Chain scission was found to promote chemicrystallization, reducing the amorphous layer thickness (l_a) and limiting plastic deformation. A critical interlamellar thickness for ductility was proposed (Fayolle et al., 2007):

$$l_a \leq 6 - 7, nm \quad (Eq. 8)$$

Below this threshold, plastic deformation cannot occur, leading to brittle failure. The study also highlighted the abrupt shift from ductile to brittle behavior once the critical molecular weight is reached (Figure 9) (Fayolle et al., 2007).
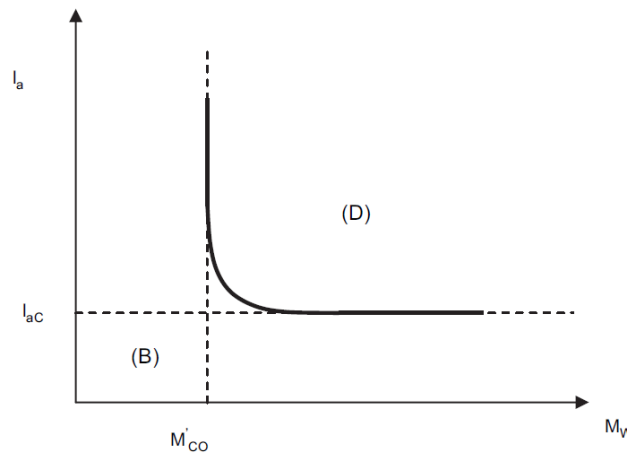
FIG. 9. Presumed schematic shape of the ductile (D) to brittle (B) transition (Fayolle et al., 2007).

The findings provide a comprehensive understanding of how oxidative degradation in PE pipes leads to embrittlement, offering criteria for predicting when PE pipes will transition from ductile to brittle failure (Fayolle et al., 2007). The study emphasizes the importance of using PE with higher molecular weight and improved oxidation resistance for enhanced durability and recommends implementing regular molecular weight tracking to anticipate and prevent embrittlement in PE pipes.

Hassinen et al. investigated the deterioration mechanisms of high-density polyethylene (HDPE) pipes exposed to chlorinated water at elevated temperatures, assessing the impact on mechanical integrity and predicting the service life of PE pipes in chlorinated environments (Hassinen et al., 2004). The study employed hydrostatic pressure testing, oxidation induction time (OIT) testing, differential scanning calorimetry (DSC), size exclusion chromatography (SEC), and fractographic analysis to comprehensively evaluate the degradation process. Rapid antioxidant loss was observed near the inner wall due to chemical reactions with chlorine, leading to localized oxidative degradation (Figure 10) (Hassinen et al., 2004). The oxidation induction time (OIT) profile showed a substantial antioxidant depletion, with chemical consumption surpassing 80% at the inner wall, indicating a significant loss of stabilizer efficiency.
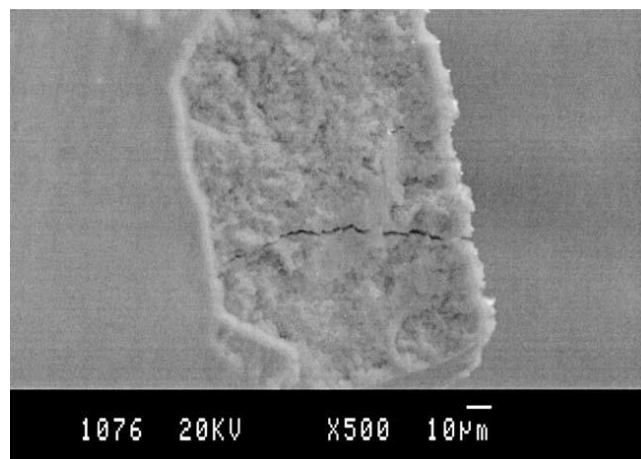

FIG. 10. Scanning electron micrograph of pipe cross-section exposed to chlorinated water (Hassinen et al., 2004).

Polymer degradation was primarily confined to the amorphous phase near the surface, creating a brittle layer vulnerable to crack initiation. The growth of the degraded layer progressed at a nearly constant rate, with oxidation primarily driven by chlorine diffusion, as described by the following equation (Hassinen et al., 2004):

$$\frac{\partial C}{\partial t} = D\nabla^2 C - kC \quad (Eq.\,9)$$

Where:

- (C): Concentration of reactive species

- (D): Diffusion coefficient

- (k): Reaction rate constant

DSC analysis revealed a significant decrease in crystallinity in degraded regions, weakening the mechanical integrity. Small axial cracks were detected at the inner pipe wall, serving as sites for slow crack growth and eventual pipe failure (Figure 11) (Hassinen et al., 2004).
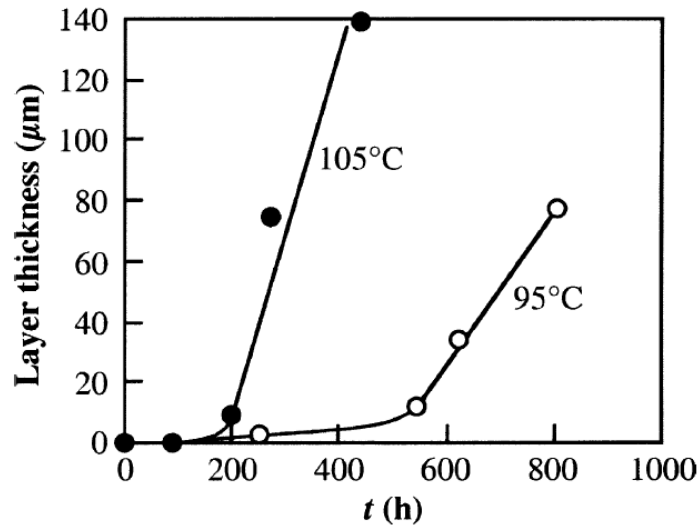

FIG. 11. Thickness of the porous material layer over time (Hassinen et al., 2004).

The study highlights the critical role of antioxidant stability in maintaining the long-term performance of PE pipes in chlorinated water environments (Hassinen et al., 2004). The findings suggest the need for enhanced stabilization strategies, such as utilizing more robust antioxidant systems or multilayer pipe designs, to delay oxidation in chlorinated environments. The authors recommend implementing routine OIT testing to assess in-service antioxidant levels and preemptively detect degradation, as well as exploring surface treatment solutions to mitigate chlorine diffusion and reduce oxidation at the pipe surface (Hassinen et al., 2004).

Sanders et al. investigated various experimental methods to evaluate the in-service life of medium-density polyethylene (MDPE) and PE80 water pipes, emphasizing the critical role of antioxidant retention in maintaining mechanical integrity over time (Sanders et al., 2009). The study employed oxidation induction time (OIT) testing, differential scanning calorimetry (DSC), infrared spectroscopy (IR), gel permeation chromatography (GPC), mechanical testing (tensile and creep),

and hydrostatic pressure testing to assess chemical and physical degradation mechanisms, including antioxidant depletion, chain scission, and oxidative damage. OIT testing revealed significant antioxidant loss near the inner wall due to chlorinated water exposure, leading to oxidation and embrittlement (Figure 12) (Sanders et al., 2009). The OIT decay equation ($Eq. 5$)
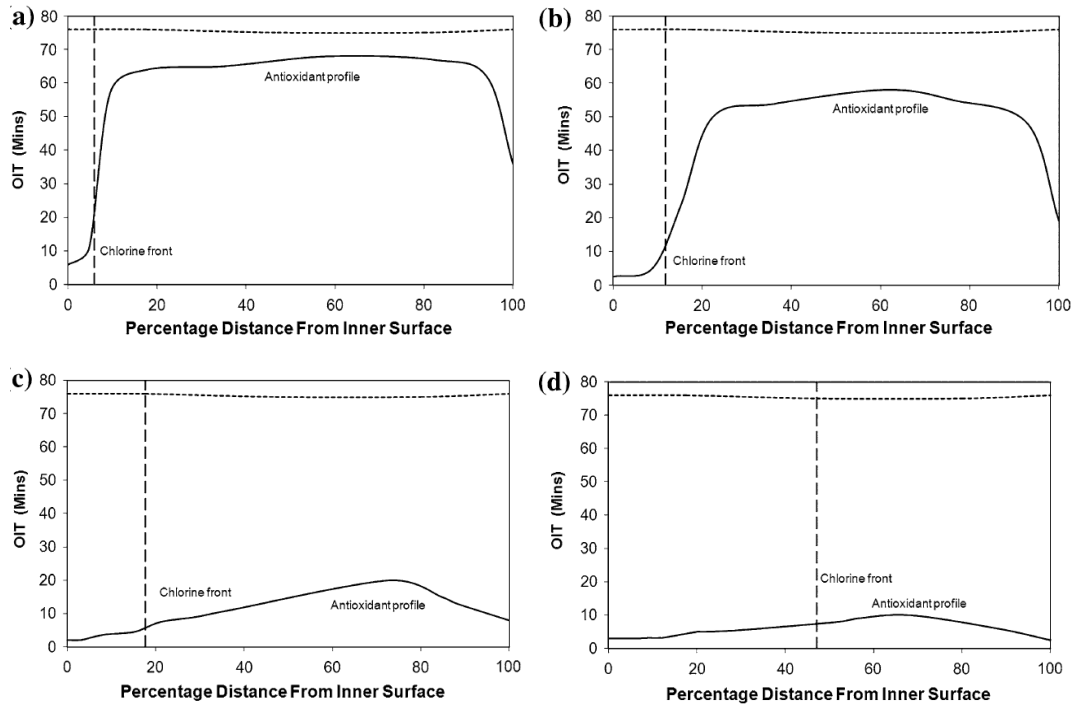

FIG. 12. Antioxidant concentration by OIT versus distance from inner wall (Sanders et al., 2009).

Mechanical testing demonstrated a decrease in yield stress and elongation at break over time as molecular weight reduced due to chain scission (Figure 13) (Sanders et al., 2009). Oxidation primarily occurred in the amorphous regions, forming brittle layers near the surface. Accelerated aging experiments estimated a PE pipe service life of approximately 50 years under standard conditions but significantly shorter under chlorinated environments. The study correlated molecular weight reduction with failure time in hydrostatic pressure tests (Sanders et al., 2009).
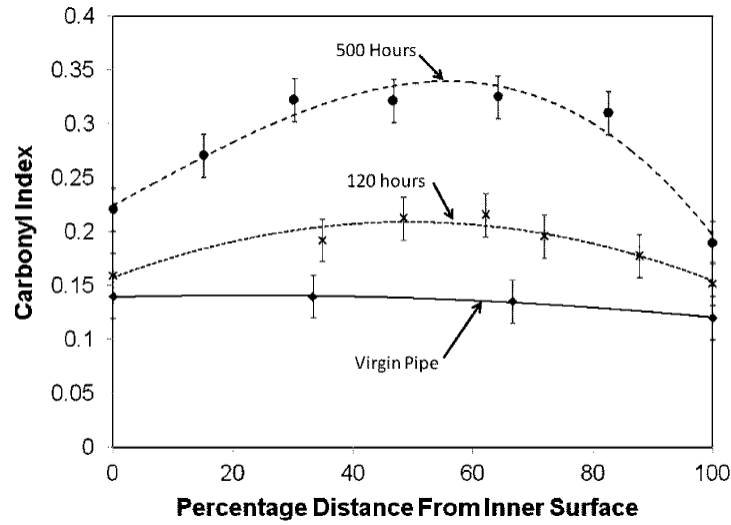
FIG. 13. Carbonyl index (ester) versus percentage distance from the inner wall (Sanders et al., 2009).

The hoop stress in the pipes was calculated using the precedent equation ($Eq.6$)

The study offers a set of chemical and mechanical evaluation techniques to assess PE pipe degradation, highlighting the critical role of antioxidant retention in prolonging PE pipe service life (Sanders et al., 2009). The findings provide empirical models to forecast failure timelines based on antioxidant depletion and mechanical property degradation. The authors recommend implementing periodic OIT testing to assess antioxidant depletion in-service, using more robust antioxidant formulations to slow degradation in chlorinated environments, and integrating chemical and mechanical assessments for accurate lifetime predictions (Sanders et al., 2009).

2.3 Coupled Chemical-Mechanical Behavior

Tripathi et al. developed a coupled chemo-mechanical model to simulate the stress corrosion cracking (SCC) behavior of high-density polyethylene (HDPE) in bleach solutions (Tripathi et al., 2021). The model integrates a morphology-based constitutive model with a diffusion-reaction kinetics model to predict static fatigue behavior, accounting for mechanical stress and chemical degradation interactions. The study employed finite element modeling (FEM) to simulate stress-life behavior under varying environmental conditions and investigated subcritical crack propagation due to stress and corrosion coupling. The proposed model distinguishes the mechanical responses of the amorphous and crystalline phases in HDPE using a morphology-based framework (Tripathi et al., 2021):

$$T = z_0 T_c + (1 - z_0) T_a \quad (Eq.10)$$

Where:

- (T): Total Cauchy stress

- (T_c): Stress in the crystalline phase

- (T_a): Stress in the amorphous phase

- (z_0): Initial crystallinity fraction

The diffusion-reaction kinetics for oxidation was modeled using the precedent equation ($Eq.9$)

Where:

- (C): Concentration of bleach

- (D): Diffusion coefficient

- (k): Reaction rate constant

The model successfully predicted the transition from ductile to brittle failure as chemical degradation progressed due to bleach-induced oxidation. Stress-life curves generated by the model revealed distinct failure regimes corresponding to stress levels and corrosion intensity (Figure 14) (Tripathi et al., 2021). FEM simulations demonstrated accelerated crack growth in regions with higher chemical degradation, confirming the role of oxidation in embrittlement (Figure 15) (Tripathi et al., 2021). The predicted results qualitatively matched experimental data, validating the model's ability to simulate SCC behavior in HDPE.
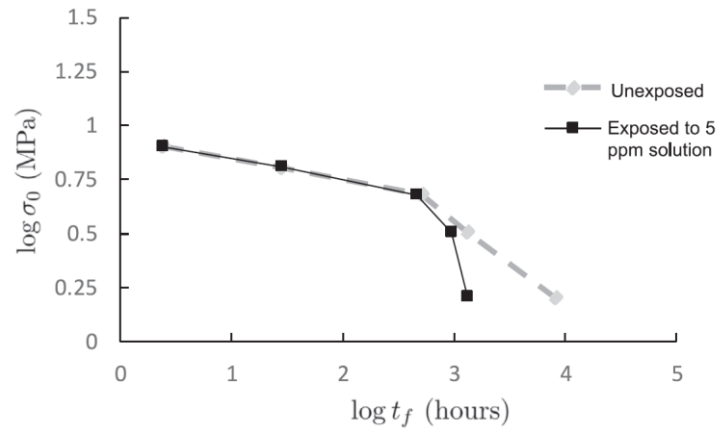

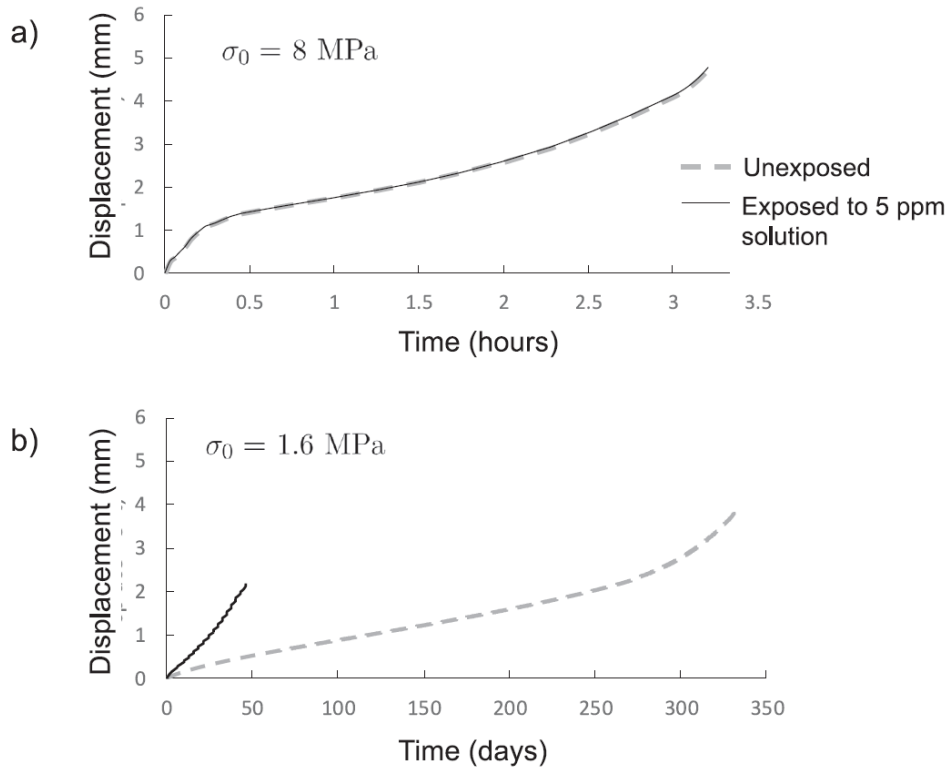*FIG. 14. Simulated stress-life curves (Tripathi et al., 2021).*

FIG. 15. Time evolution of cross-head displacement with and without bleach exposure (Tripathi et al., 2021)

The study highlights the importance of integrating chemical degradation effects in predictive models for accurate lifetime assessment of PE pipes exposed to aggressive environments (Tripathi et al., 2021). The authors recommend further research to extend the model to field conditions, accounting for multiple environmental stressors, and to explore material enhancements such as chemical stabilizers and structural modifications to mitigate oxidation-induced failures in PE pipes (Tripathi et al., 2021).

Boujlal analyzed slow crack initiation in old polyethylene resins using an elasto-visco-plastic rheological model, combining experimental and numerical approaches (Boujlal, 2012). The study provided insights into how aging affects the mechanical properties and crack resistance of PE pipes. The elasto-visco-plastic strain rate was modeled as:

$$\dot{\epsilon} = \dot{\epsilon}e + \dot{\epsilon}vp \quad (Eq.\,11)$$

Where:

- $(\dot{\epsilon}_e)$: Elastic strain rate

- $(\dot{\epsilon}_{vp})$: Visco-plastic strain rate

Frank et al. investigated the prediction of remaining lifetime of polyethylene pipes after extended service periods, developing a methodology based on fracture mechanics testing and numerical simulation (Frank et al., 2009). The study combined experimental data from aged pipes with finite

element analysis to create a comprehensive lifetime prediction model. The critical stress intensity factor was defined as:

$$K_c = \sigma_c \sqrt{\pi a} F(a/W) \quad (Eq.\,12)$$

Where:

- (σ_c): Critical stress

- (a): Crack length

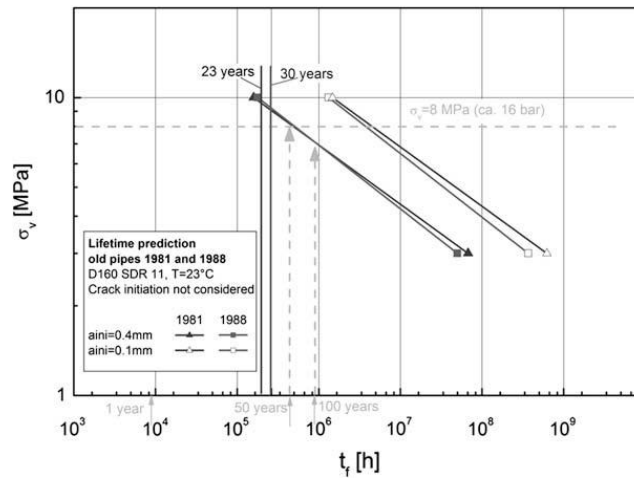- $(F(a/W))$: Geometric correction factor

- (W): Specimen width

FIG. 16. Comparison of predicted and experimental lifetime data for aged PE pipes (Frank et al., 2009).

2.4 Advanced Lifetime Prediction Methods

Hoàng and Lowe presented a comprehensive methodology for predicting the service lifetime of blue PE100 water pipes under hydrostatic pressure in chlorinated environments (Hoang & Lowe, 2008). The approach integrates hydrostatic pressure testing, antioxidant depletion analysis, and thermo-oxidative degradation assessment to estimate the long-term durability of PE100 pipes. The study evaluated pipe performance under constant internal pressure at various temperatures (20°C–80°C) and assessed antioxidant depletion using oxidation induction time (OIT) testing. Rapid depletion of antioxidants at the pipe's inner wall was observed, leading to localized oxidative degradation. Higher testing temperatures (80°C) accelerate d antioxidant consumption and oxidation, correlating with reduced pipe lifespan. OIT thermograms showed antioxidant depletion over increasing exposure times (Figure 17) (Hoang & Lowe, 2008).
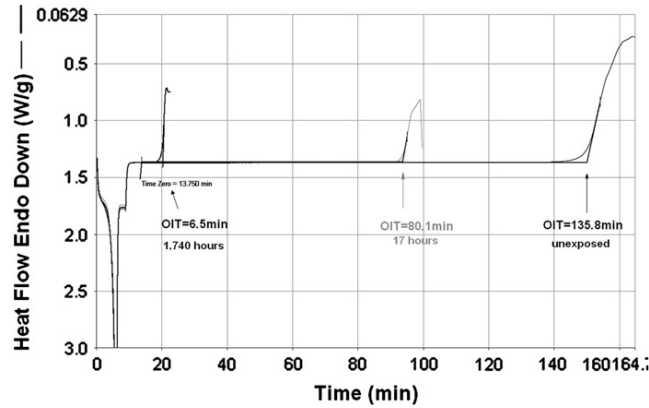
FIG. 17. Typical OIT thermograms of pipes tested at 80°C (Hoang & Lowe, 2008).

The OIT reduction over time is modeled as:

$$OIT(t) = OIT_0 \cdot e^{-kt} \quad (Eq.\,5)$$

Hydrostatic testing revealed ductile failure at high stress levels (Stage I) and brittle failure due to chemical degradation at lower stresses (Stage III), as illustrated in the stress rupture curve (Figure 18) (Hoang & Lowe, 2008).
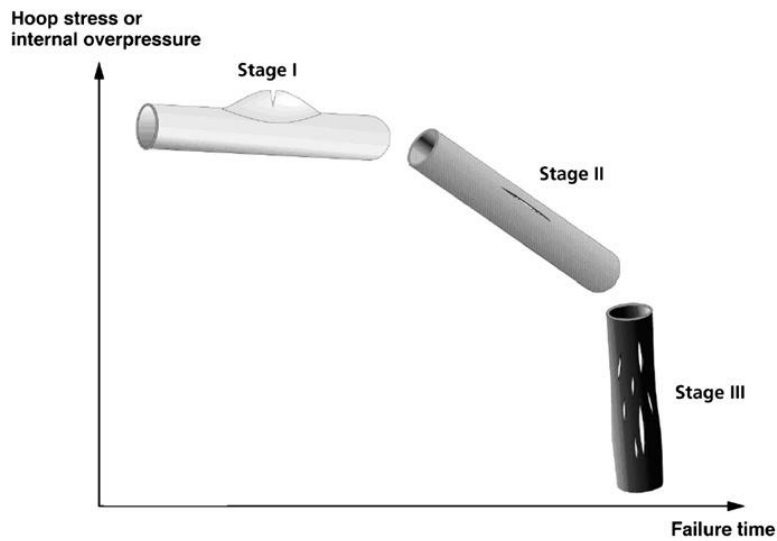

FIG. 18. Stress rupture schematic (Hoang & Lowe, 2008).

The hoop stress in the pipes was calculated using the precedent equation ($Eq.\,6$)

An Arrhenius-based modeling approach was employed to extrapolate service life, revealing that chlorinated water exposure reduces pipe lifetime by 10–30 times compared to non-chlorinated conditions (Figure 19) (Hoang & Lowe, 2008).
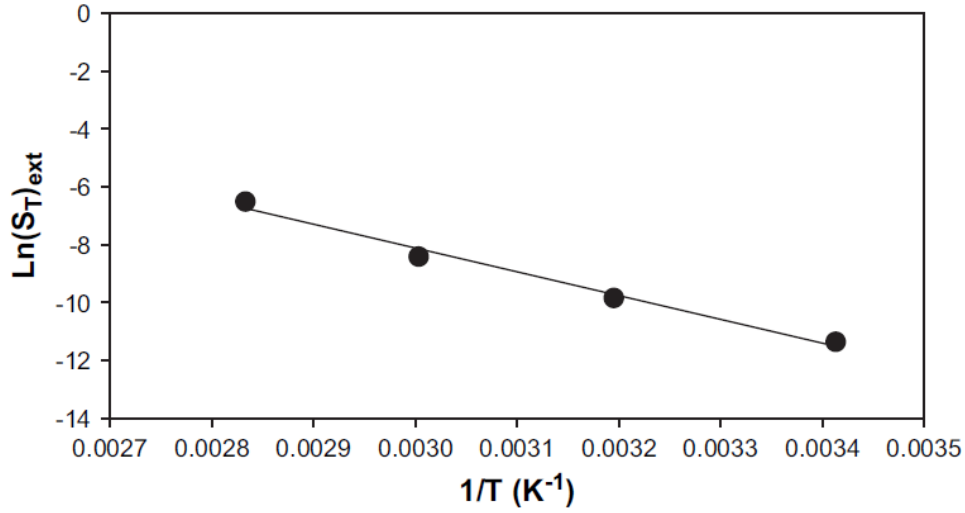
FIG. 19. Arrhenius plot for OIT data for the external surface of the pipe (Hoang & Lowe, 2008).

The Arrhenius lifetime prediction equation is given by (Hoang & Lowe, 2008):

$$t_f = A \cdot e^{\frac{E_a}{RT}} \quad (Eq.\,13)$$

Where:

- (t_f): Predicted lifetime

- (A): Pre-exponential factor

- (E_a): Activation energy

- (R): Gas constant

- (T): Absolute temperature (K)

The study offers a scientifically validated model combining mechanical and chemical degradation data to predict PE100 pipe lifespan, highlighting the need for effective antioxidant stabilization to mitigate oxidation-induced failure (Hoang & Lowe, 2008). The findings emphasize how operational temperatures significantly affect the degradation rate and service life of PE pipes. The authors recommend developing PE100 pipes with improved antioxidant packages to extend service life in chlorinated water systems, implementing regular OIT testing for early detection of antioxidant depletion and degradation risk, and minimizing high-temperature exposure during installation to delay oxidation onset (Hoang & Lowe, 2008).

Hutař et al. introduced a numerical methodology grounded in Linear Elastic Fracture Mechanics (LEFM) to estimate the lifetime of high-density polyethylene (HDPE) pressure pipes (Hutař et al., 2011). The approach combines numerical calculations of stress intensity factors (SIFs) under various loading conditions with experimental data on creep crack growth kinetics to predict service life. The study applied LEFM to analyse slow crack growth (SCG) in HDPE pipes, focusing on region B of the hoop stress-failure time curve (Figure 20) (Hutař et al., 2011).
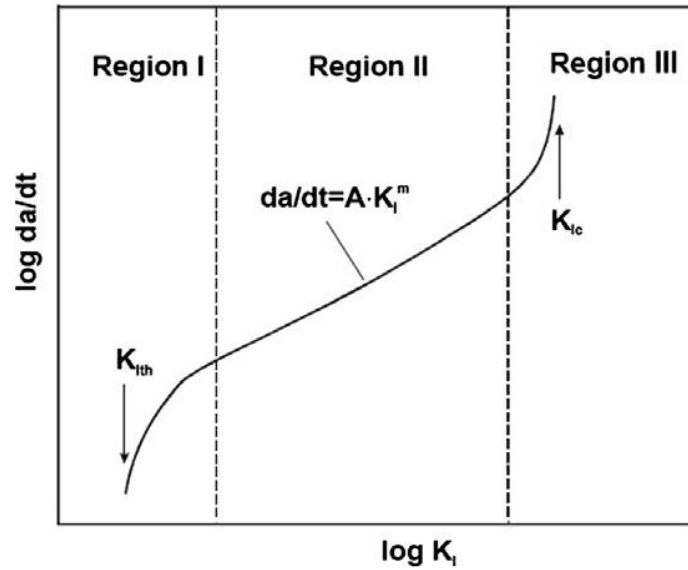
FIG. 20. Scheme of creep crack growth rate curve (Hutař et al., 2011).

Detailed 3D models with refined mesh around crack tips were used to simulate the stress intensity factors (SIFs) and crack propagation under internal pressure. The stress intensity factor (SIF) for mode I loading was calculated using the following equation (Hutař et al., 2011):

$$K_I = \sigma\sqrt{\pi a}Y(a/s) \quad (Eq.\,14)$$

Where:

- (σ): Applied stress

- (a): Crack length

- $(Y(a/s))$: Geometric factor (numerically derived)

The creep crack growth rate was described using the following equation (Hutař et al., 2011):

$$\frac{da}{dt} = A \cdot (K_I)^m \quad (Eq.\,15)$$

Where:

- $(A)\ and\ (m)$: Material-specific constants

- (K_I): Stress intensity factor

The time to failure was estimated using the following equation (Hutař et al., 2011):

$$t_f = \int_{a_0}^{a_f} \frac{da}{A \cdot \left(K_I(p_{int}, d, s, a)\right)^m} \quad (Eq.\,16)$$

Where:

- (a_0): Initial crack length

- (a_f): Final crack length

The developed methodology accurately predicted the lifetime of HDPE pipes under internal pressure, validated by experimental data. 3D FEM modeling provided significantly more accurate SIF values compared to 2D models, highlighting the importance of considering realistic pipe geometries (Figure 21) (Hutař et al., 2011).
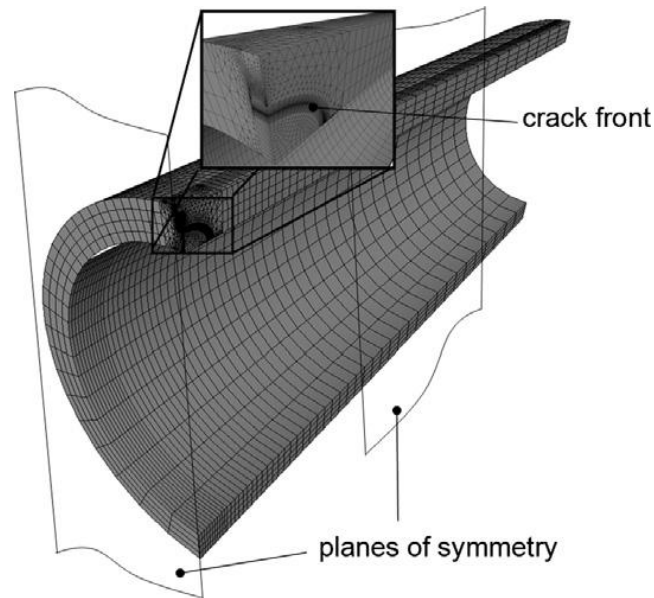

FIG. 21. Finite element model of the internally pressured pipe with crack (Hutař et al., 2011).

Crack growth rate and lifetime predictions were found to be sensitive to internal pressure, pipe geometry, and material creep properties (Figure 22) (Hutař et al., 2011).
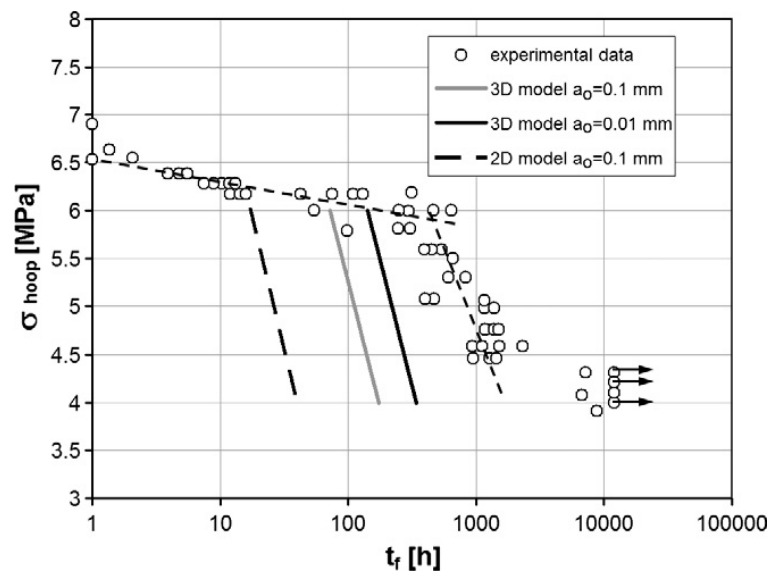

FIG. 22. Comparison of experimental data with numerical simulations (Hutař et al., 2011).

The study introduced a quantitative and validated method for predicting HDPE pipe failure due to slow crack growth, crucial for modeling pipe degradation (Hutař et al., 2011). The research provided a framework to incorporate mechanical stress analysis with experimental creep data, enhancing lifetime prediction accuracy. The authors suggested the use of advanced 3D FEM models for realistic assessment of crack behavior, which can be applied to study the effect of mechanical damage (e.g., punching) on PE pipes. They recommended integrating the presented LEFM-based modeling approach with experimental SCG data for more precise lifetime predictions, using 3D FEM simulations to investigate stress concentration effects due to localized damage, and expanding the model to include coupled chemo-mechanical degradation for a comprehensive assessment of PE pipe durability (Hutař et al., 2011).

Scholten et al. evaluated the reliability of detergents used in accelerated slow crack growth (SCG) testing of polyethylene (PE) pipe materials, comparing Nonylphenol Ethoxylate (NPE) detergents with Teepol™ (Scholten et al., 2001). The research demonstrated significant issues with NPE detergent degradation, which affected testing consistency and lifetime predictions. The study employed Full Notch Creep (FNC) Testing and Cone Testing methodologies while monitoring chemical stability through pH and conductivity measurements. The stress intensity factor (SIF) for crack growth was described by:

$$K_I = \sigma\sqrt{\pi a}\, Y(a/s) \quad (Eq.\,17)$$

Where:

- (σ): Applied stress

- (a): Crack length

- $(Y(a/s))$: Geometric factor

The research revealed that NPE detergents exhibit significant oxidation, leading to an increase in acidity $(over\ 10^5\ times)$ and conductivity within 10 days at 80°C, causing variability in crack growth rates. The detergent degradation rate followed (Scholten et al., 2001):

$$pH(t) = pH_0 + k \cdot t \quad (Eq.\,18)$$

Where:

- (pH_0): Initial pH

- (k): Degradation rate constant

- (t): Time

Poduška et al. investigated how specimen size affects the determination of tangential and axial residual stresses in polymer pipes (Poduška et al., 2013). The study employed the Ring Deformation Method and Layer Removal Technique, validated through 3D FEM simulations. The research revealed that tangential residual stresses in polymer pipes typically range between 1.5–4 MPa. The correction function for deformation was expressed as (Poduška et al., 2013):

$$\frac{\Delta D_{ps}}{\Delta D_L} = 1.097 \left(\frac{L}{s}\right)^{-0.5} \quad (Eq.\,19)$$

Where:

- (ΔD_{ps}): Deformation for plane strain conditions

- (ΔD_L): Measured deformation for specimen length (L)

- (s): Wall thickness

The study demonstrated that axial residual stresses significantly influence tangential stress measurements in larger specimens but are negligible in thin rings $((L/s < 2))$ (Poduška et al., 2013).

He et al. examined the impact of short chain branch distribution (SCBD) on the fracture behavior and SCG resistance of unimodal and bimodal HDPE pipe resins (He et al., 2018). The research utilized Temperature Rising Elution Fractionation (TREF) and High-Temperature Gel Permeation Chromatography (HT-GPC) to analyze branching effects. The crack growth rate was modeled using (He et al., 2018):

$$\frac{da}{dt} = A \cdot (K_I)^m \quad (Eq.\,20)$$

Where:

- $(A)\ and\ (m)$: Material-specific constants

- (K_I): Stress intensity factor

Show Image

The study found that resins with more uniformly distributed SCBs formed fewer brittle fracture zones and maintained better ductility under stress, providing crucial insights for improving PE pipe performance through molecular architecture design (He et al., 2018).

These papers contribute significant methodological advances and fundamental understanding to the field of PE pipe lifetime prediction, particularly in addressing the combined effects of chemical and mechanical degradation mechanisms.

3. Démarche scientifique/Scientific approach

To investigate the factors contributing to the premature failure of PE pipes under point loading, this study will focus on determining whether failures are caused by external damage resulting from mechanical stresses, such as point loading, or if they can be attributed to chemical degradation caused by chlorinated disinfectants and how these factors may jointly influence this phenomenon. The scientific approach is divided into three phases:

Phase 1: Computational Modeling

- Utilize the ABAQUS finite element software to create precise models of PE pipes and simulate various point load scenarios accurately. By adjusting factors like the shape and dimensions of the punch, punching depth, pipe dimensions, and internal water pressure, real-life mechanical pressures on the pipes can be replicated.

- Conduct FEA analysis to compute stress and strain distribution within the pipes' structure, focusing on the initiation and propagation of fractures caused by point loading. These

findings will offer insights into how well PE pipes withstand mechanical pressure and aid in estimating their durability under different stress conditions.

- Perform a parametric analysis to identify critical damage conditions, exploring various parameters to understand the thresholds for damage occurrence. Propose effective solutions aimed at reducing or preventing damage through innovative approaches, involving damage modeling to develop comprehensive models that depict the behavior of the pipes under diverse stress situations.

Phase 2: Chemical Degradation Assessment: Effects of Chlorine Disinfection

- Investigate the effects of chlorinated disinfectants on the stability and longevity of PE pipes. Predict how various levels of chlorination affect PE pipes over time by observing changes in material properties and degradation mechanisms.

- Conduct physical and chemical characterization tests on materials, as well as assess mechanical properties at different levels of degradation under chlorine exposure.

Phase 3: Lifetime Prediction: Combined Influence of Punching and Chemical Degradation

- Combine the findings from the study of mechanical stresses and chemical degradation to predict the lifetime of PE pipes more accurately. Use the data from both these analyses to create models that can simulate the combined effects of point loading and chemical exposure over time.

- Study how continuous chemical attack affects the material properties of the PE pipes when subjected to mechanical point loading.

- Employ multi-physical problem solving by solving for the interaction between chemical and mechanical degradation. Identify factors that most significantly reduce the pipes' service life and under what conditions.

- Develop a predictive model aimed at forecasting the point of failure more accurately, allowing for early interventions to improve pipe durability and reliability.

4. Concluding Remarks

This bibliographic report provides a comprehensive overview of the current state of research on the degradation mechanisms and lifetime prediction of polyethylene (PE) pipes used in drinking water distribution networks, with a specific focus on the combined effects of mechanical stress from point loading and chemical degradation due to chlorinated disinfectants.

The report summarizes the key findings and methodologies employed in studies addressing chemical degradation mechanisms, property evolution during chemical attack, coupled chemical-mechanical behavior, and advanced lifetime prediction methods for PE pipes. It highlights the importance of understanding the intricate interplay between mechanical stress and chemical degradation in predicting the long-term performance and durability of PE pipes.

Several studies have investigated the chemical degradation mechanisms of PE pipes exposed to chlorine dioxide and other disinfectants, revealing the critical role of antioxidant depletion, oxidative degradation, and embrittlement in reducing pipe service life. The impact of chlorine exposure on the mechanical and chemical integrity of PE pipes has been extensively studied, with researchers

employing various experimental techniques such as tensile testing, oxidation induction time (OIT) testing, differential scanning calorimetry (DSC), and infrared spectroscopy (IR) to assess degradation processes.

Coupled chemo-mechanical models have been developed to simulate the stress corrosion cracking behavior of PE pipes in aggressive environments, integrating mechanical stress and chemical degradation interactions. These models provide valuable insights into the failure mechanisms and crack propagation kinetics of PE pipes under combined loading conditions.

Advanced lifetime prediction methods, such as the Arrhenius-based extrapolation, Ultimate Strain Extrapolation Method (USEM), and Distortion Energy Extrapolation Method (DEEM), have been proposed to overcome the limitations of traditional stress-based approaches. These methods incorporate strain and energy-based failure criteria, offering more accurate and conservative predictions of PE pipe service life.

The report also emphasizes the importance of material selection, with studies highlighting the superior slow crack growth resistance and deformation recovery capabilities of PE100-RC grades compared to traditional PE100 materials. The influence of short chain branch distribution (SCBD) on the fracture behavior and mechanical performance of PE pipe resins has been investigated, providing guidance for the development of more durable and reliable PE pipe systems.

In conclusion, this bibliographic report serves as a comprehensive resource for understanding the current state of research on the degradation mechanisms and lifetime prediction of PE pipes in drinking water distribution networks. It provides valuable insights into the combined effects of mechanical stress and chemical degradation, highlighting the need for advanced modeling techniques, material enhancements, and improved testing methodologies to ensure the long-term performance and reliability of PE pipe systems. The findings and recommendations presented in this report will inform the development of strategies for the prevention, improvement, and maintenance of PE pipes, ultimately contributing to the safe and efficient operation of drinking water distribution networks.

5. Bibliographie/ References

Handbook of PE Pipe, 2nd edition, Plastics Pipe Institute (PPI), 2008, pp. 43-103.

J. Lenz, "Long-Term Point Loads Testing with Plastic Pipes," 11th plastic pipe conference, PPXI, Munich, Germany, 2001.

Dossier technique conduit 9010 RC en PE 100-RC.

X. Colin, L. Audouin, J. Verdu, M. Rozental-Evesque, B. Rabaud, F. Martin, F. Bourgine, "Aging of Polyethylene Pipes Transporting Drinking Water Disinfected by Chlorine Dioxide. I. Chemical Aspects," Polymer Engineering and Science, vol. 49, no. 7, pp. 1429-1437, 2009.

W. Yu, B. Azhdar, D. Andersson, T. Reitberger, J. Hassinen, T. Hjertberg, U.W. Gedde, "Deterioration of polyethylene pipes exposed to water containing chlorine dioxide," Polymer Degradation and Stability, vol. 96, pp. 790-797, 2011.

J.P. Dear, N.S. Mason, "Effect of chlorine on polyethylene pipes in water distribution networks," Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, vol. 220, no. 3, pp. 97-111, 2006.

J. Hassinen, M. Lundbäck, M. Ifwarson, U.W. Gedde, "Deterioration of polyethylene pipes exposed to chlorinated water," Polymer Degradation and Stability, vol. 84, no. 2, pp. 261-267, 2004.

J.M.B. Sanders, M.A. Shepherd, H.M.S. Belmonte, J.P. Dear, "Methods for determining the in-service life of polymer water pipes," Journal of Materials Science, vol. 44, pp. 4683-4691, 2009.

O.Y. Elagina, A.V. Buryakin, N.S. Poches, "Influence of service life on physical and mechanical characteristics of polyethylene pipes," AIP Conference Proceedings, vol. 1876, no. 1, 020061, 2017.

X. Zheng, X. Zhang, L. Ma, W. Wang, J.G. Yu, "Mechanical characterization of notched high density polyethylene (HDPE) pipe: Testing and prediction," International Journal of Pressure Vessels and Piping, vol. 173, pp. 11-19, 2019.

B. Fayolle, X. Colin, L. Audouin, J. Verdu, "Mechanism of degradation induced embrittlement in polyethylene," Polymer Degradation and Stability, vol. 92, no. 2, pp. 231-238, 2007.

J. Hassinen, M. Lundbäck, M. Ifwarson, U.W. Gedde, "Deterioration of polyethylene pipes exposed to chlorinated water," Polymer Degradation and Stability, vol. 84, no. 2, pp. 261-267, 2004.

J.M.B. Sanders, M.A. Shepherd, H.M.S. Belmonte, J.P. Dear, "Methods for determining the in-service life of polymer water pipes," Journal of Materials Science, vol. 44, pp. 4683-4691, 2009.

A. Tripathi, S. Mantell, J.L. Le, "Chemo-mechanical modeling of static fatigue of high density polyethylene in bleach solution," International Journal of Solids and Structures, vol. 217-218, pp. 90-105, 2021.

A. Boujlal, "Analysis of Slow Crack Initiation of Old Polyethylene Resins by Means of an Elasto-Visco-Plastic Rheological Model: Experimental and Numerical Approach," Plastic Pipes XVI, Barcelona, Spain, 2012.

A. Frank, G. Pinter, R.W. Lang, "Prediction of the remaining lifetime of polyethylene pipes after up to 30 years in use," Polymer Testing, vol. 28, pp. 737-745, 2009.

E.M. Hoang, D. Lowe, "Lifetime prediction of a blue PE100 water pipe," Polymer Degradation and Stability, vol. 93, no. 8, pp. 1496-1503, 2008.

P. Hutař, M. Ševčík, L. Náhlík, G. Pinter, A. Frank, I. Mitev, "A numerical methodology for lifetime estimation of HDPE pressure pipes," Engineering Fracture Mechanics, vol. 78, no. 17, pp. 3049-3058, 2011.

F.L. Scholten, D. Gueugnaut, F. Berthier, "A More Reliable Detergent for Cone and Full Notch Creep Testing of PE Pipe Materials," 11th Plastic Pipes conferences, PPXI, Munich, Germany, 2001.

J. Poduška, J. Kučera, P. Hutař, M. Ševčík, J. Křivánek, J. Sadílek, L. Náhlík, "The Effect of Specimen Size on the Determination of Residual Stress in Polymer Pipe Wall," Engineering Fracture Mechanics, vol. 108, pp. 98-109, 2013.

X. He, X. Zha, X. Zhu, X. Qi, B. Liu, "Effect of short chain branches distribution on fracture behavior of polyethylene pipe resins," Polymer Testing, vol. 68, pp. 219-228, 2018.