Thermal-Oxidative Ageing and Lifetime Prediction of the High-Density Polyethylene Pipes

Ihssan Srii, Naoual Belouaggadia, Mustapha Jammoukh, Latifa El Farissi, and Abdellah Zamma

Abstract Polyethylene (PE) pipes are widely used in drinking water distribution networks around the world. In-depth research into the ageing of PE pipes is imperative to ensure their successful use. The study of the ageing of these products is based on the analysis of the kinetics and mechanisms of failure during prolonged exposure to external factors. Understanding polymer degradation mechanisms is crucial for developing stabilisation strategies and predicting lifetimes based on accelerated artificial ageing tests. The aim of this article is to detail the methodology used to predict the service life of high-density polyethylene (HDPE) pipes. Reliable predictions of the service life of underground HDPE pipes must be based on a thorough understanding of the failure mechanisms and on more reliable extrapolation procedures, allowing the transition from relatively short-term test data to long-term service environments.

Keywords High density polyethylene (HDPE) · Lifetime · Prediction · Ageing

1 Introduction

The development of plastics today is driving economic development and offering great benefits to our lives. Plastics are essential to the development of modern civilisation and are increasingly replacing traditional materials in almost every area of

I. Srii (✉) · N. Belouaggadia · A. Zamma
Laboratory of Modeling and Simulation of Intelligent Industriel Systems M2S2I, Higher Normal School of Technical Education Mohammedia (ENSETM), University of Hassan II Casablanca, Mohammedia, Morocco
e-mail: ihssan.srii-etu@etu.univh2c.ma

I. Srii · M. Jammoukh · L. El Farissi
Technical Center of Plastics and Rubber (CTPC), Casablanca, Morocco

N. Belouaggadia
Builders la, Builders Engineering School, Comue University of Normandy, 1 Rue Pierre Et Marie Curie, 14610 Epron, France

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packaging, construction and industry. Plastics are essential to the development of modern civilisation and are replacing traditional materials in almost all areas of packaging, construction and industry. These materials are characterised by high durability, simple processing, low weight and low production costs for large, ready-to-use products.

Thermal and oxidative ageing studies of high-density polyethylene (HDPE) highlight the impact of these processes on material properties. For example, Jong-Il Weon [1] presented a study to assess how thermal aging affects mechanical and thermal behavior and fundamentally understand the degradation mechanism of linear low-density polyethylene (LLDPE) pipes, samples were degraded by thermal oxidation. Thermal aging was carried out at 100 °C for 720, 2400, 6000 and 7200 h. Methods for improving the durability and reliability of LLDPE pipes under operating conditions are likely to emerge. Numerous technical methods, such as DSC, OIT, TGA and FT-IR, have been used to quantify the degree of thermal degradation. M. rozental-evesque and all [2] presented a study on the ageing of polyethylene pipes used to transport drinking water in the presence of chlorine disinfectant. It describes not only the physico-chemical properties of the materials used, but also the effects of chlorine on their structure and performance. Colin et al. [3] studied the ageing of polyethylene pipes carrying drinking water disinfected with chlorine dioxide. Guo et al. [4] examined the safety of high-density polyethylene (HDPE) pipes subjected to thermal damage. Thermal aging experiments were conducted to obtain specimens containing thermal damage. Changes in mechanical properties and microstructure were studied by means of various characterization analyses. The effect of exposure temperature, heating time and cooling method on mechanical properties was investigated, respectively.

In addition, a multi-scale approach is used to assess the effects of thermo-oxidative aging on HDPE used in civil engineering and construction applications. These studies highlight the importance of understanding the aging mechanisms of HDPE to assess the evolution of its mechanical and structural properties [5–9]. However, when it comes to predicting the service life of HDPE pipes, it is important to note that the service life of a material depends on many factors, including conditions of use, temperature, pressure, and material quality, and can therefore vary from one application to another.

A large number of research studies have developed specific protocols for inducing accelerated ageing of polyethylene (PE) pipes. These studies implemented a variety of experimental conditions, manipulating parameters such as time, internal pipe pressure and water temperature [10–14]. The aim was to deliberately accelerate the ageing process on PE samples, enabling faster and more in-depth assessment of material performance and durability.

For the past few years, the prediction of polymer lifetime has been a major concern for researchers, materials producers and users [10–12, 15–19].

In this contribution, we have summarized the basic concept of thermo-oxidative ageing of PE pipes and reviewed research into methods for predicting the lifetime of HDPE pipes. We then summarized some methods for the characterisation of PE pipes after aging according to international standards. Next, we discussed trends in PE pipe lifetime prediction, and gave an overview of the future development of HDPE pipes prediction methods in terms of artificial intelligence. Finally, we proposed the use of machine learning models for lifetime prediction.

2 Lifetime Prediction

There is a direct relationship between the degradation mechanisms of plastic pipes and their lifetime. Different degradation mechanisms will affect different properties of plastic pipes, such as mechanical properties, physical properties and chemical properties, reducing the service life of plastic pipes. Predicting the service life of PE pipes generally takes into account the ageing of the material.

Koga et al. [20] analyzed the degradation behavior of PVC resins under elevated temperature conditions using Fourier transform infrared spectroscopy (FTIR), tensile tests and small punch (SP) tests. Based on the results of these tests, they compared the activation energies and lifetimes estimated using the Arrhenius method.

Marton Bredàcs et al. [21] predicted the residual service life of small-diameter polyethylene pipes. The properties and lifetime of four small-diameter PE water pipes for domestic supply were studied, and to predict the residual lifetime of the pipes with regard to thermo-oxidative ageing of the materials, a traditional Arrhenius concept was applied. On the basis of the measured data, all products are expected to meet or exceed the predicted service life of 50 years.

Wang et al. [12] presented a model to predict the lifetime of polyethylene (PE) natural gas pipes aged with different internal pressures using d thermo-oxidative aging tests (TOA). The Arrhenius relationship is interpreted as a linear correlation between the oxidation induction time (OIT) (logarithmic scale) and the inverse of temperature (1/T) at different test temperatures. Lifetime predictions in the range 0 to 0.4 MPa at 20 °C were found to exceed the 50-year lifetime requirement. This method was confirmed by the authors as being highly suitable for pressurized PE city gas pipes, and also for other plastic pipes under similar conditions.

Methods for assessing the service life of polyethylene pipes include accelerated aging tests, constant stress tests, stress tests and prediction models based on empirical equations and numerical simulations, Zha et al. [11] reviewed the different methods used to predict the service life of polyethylene pipes, as well as the limitations and current trends in this field, with the authors examining several methods for predicting the service lifetime of polyethylene pipes, notably; accelerated ageing tests and mathematical models are used to predict the service life of polyethylene pipes as a function of various parameters, such as temperature, pressure and environmental stresses,, S. Zha points out that each of these methods has advantages and limitations, and that it is important to understand these limitations when assessing the reliability of polyethylene pipe service life predictions.

Therefore, thermo-oxidative ageing tests of HDPE pipes to determine their lifetime are based on the hypothesis that degradation follows an Arrhenius relationship with a significant temperature dependence [18, 22, 23], A method for predicting the lifetime of polyethylene gas pressure pipes using a thermo-oxidative ageing test and a tensile test has been proposed[16]. Alimi et al. [24] studied the mechanical properties of extruded PEHD-80 pipe walls for natural gas distribution, in which case Alimi defined that PE pipe service life prediction is genera-ally based on pressure tests.

Plastic polyethylene pipes, and more specifically polyethylene (HDPE) pipes, are generally evaluated in terms of service life using hydrostatic pressure tests, where the rupture time is measured as a function of internal pressure. The ASTM D-2837 and ISO 9080 standards have been developed and validated to determine the long-term performance of plastic pipes, based respectively on hydrostatic testing and the minimum strength required.

Predicting the lifetime of polyethylene pipes remains a major challenge, due to the limitations of current methods and the variability of operating conditions. Further efforts are needed to develop more accurate prediction methods and to collect long-term data on polyethylene pipe performance.

2.1 Regression Model

The accelerated aging test was based on aging kinetics to predict the service life of PE pipes. The dynamic curve linearization method is used to predict service life because it is reliable, fast and can calculate changes in aging properties over time [10, 11, 13, 14, 17, 21].

The prediction algorithm is as follows:

$$f(p) = Ae^{-Kt}$$

A: constant

With P;

$$P = f(p) = \frac{s}{s_0} = \frac{OITavantlevieillissement}{OITaprèsvieillissement}$$

With: OIT is the Oxidation induction time.

According to the Arrhenius extrapolation formula, the rate-of-change constant K and the temperature T obey the Arrhenius equation, which is equation;

$$K = Ze^{-\frac{E}{RT}}$$

Finally, the lifetime calculated by;

$$t = \frac{\ln\left(\frac{A}{P}\right)}{K}$$

2.2 Thermo-oxidative Ageing (TOA)

Thermo-oxidative ageing of HDPE pipes is a process during which the material is affected by heat and oxygen, which can alter its physical and chemical properties over time [5, 14, 25]. A study has shown that HDPE is sensitive to oxidative aging, which can affect its macromolecular and crystalline structure, as well as its mechanical properties. This aging process can involved the loss of antioxydants and have an impact on the materials strength. It is therefore important to take thermo-oxidative aging into account when using HDPE pipes, particularly with regard to longterm applications and environmental conditions [11, 12, 18].

The thermo-oxidative ageing of water in air is an approach for studying the ageing of HDPE pipes, and for carrying out this study by proposing specific conditioning linked to the various parameters impacting on these products, such as time, temperature and pressure. The experimental platform consists of a thermal aging test oven, a pressure pomp, two nipples and a main connection line as shown in Fig. 1 (5), a pressure applied to the HDPE sampling pipe that exists inside the oven by the main line that generates this pressure from the pomp.

Fig. 1 The experimental platform experimental of the thermal oxidative aging test of pressured PE pipes (1-Pressure pomp, 2-Oven, 3-Connection line, 4-Pipe PE100, 5-Nipple (laboratory-CTPC)

3 Characterization of Polyethylene Pipes

The aim of characterisation is to develop an accurate and scientific description of the state of samples subjected to defined stress conditions. The parameters most frequently used to characterise polyethylene samples following a chemical–mechanical ageing test as follows:

- Oxidation induction time (OIT), determined by differential scanning calorimetry (DSC) according to ISO 11357 standard [26].
- Tensile strength based on tensile test according to EN ISO 6259 standard [27].

4 Conclusion

This study of the thermal-oxidative ageing and service life prediction of high-density polyethylene (HDPE) pipes make it clear that this issue represents an essential area of research with significant implications for various industrial sectors.

The numerous studies analyzed consistently underline the decisive influence of thermal and oxidative conditions on the durability of HDPE pipes. The ageing mechanisms identified, such as chemical degradation and crack formation, have been corroborated by several sources, underlining the critical importance of understanding these processes to ensure the long-term performance of HDPE infrastructures.

Advances in service life prediction, while promising, require a holistic approach that takes into account the variability of environmental conditions. Current models provide valuable tools for maintenance planning, but it is clear that further research is needed to refine these models and make them more specific to real-life applications.

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