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ARTICLE

Aging and Degradation Patterns and Life Prediction of Polyethylene Pipes Under Thermal Oxidation and Photo-Oxidation Effects

Yaoying Yue[1], Yang Wang[1,*], Nan Lin[2,*], Xingze Sun[2], Bin Sun[1], Dong Wang[3] and Zongjie Zhou[1]

[1]School of Mechanical Engineering, Xinjiang University, Urumqi, China
[2]Pressure Pipe Department, China Special Equipment Inspection and Research Institute, Beijing, China
[3]Karamay City Bestar Technology Development Co., Ltd., Karamay, China

*Corresponding Authors: Yang Wang. Email: wy830052@126.com; Nan Lin. Email: sy_linnan@163.com

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ABSTRACT: Polyethylene (PE) pipes are widely used in various gas transmission applications due to their excellent flexibility and other advantages. As high-molecular-weight non-metallic polymeric materials, they inevitably undergo degradation and aging during service under the action of environmental factors such as temperature and ultraviolet (UV) radiation, which impairs their service performance. To investigate the effects of environmental factors on the aging and degradation of PE pipes, a reliable method for predicting their service life was developed in this study. Taking PE80 DN110 pipes as the research subject, an accelerated aging method was adopted to simulate the combined effects of thermo-oxidative and photo-oxidative aging on the pipes. By using Fourier Transform infrared spectroscopy (FTIR) to test and track the carbonyl index (CI), the aging mechanism is explored. Oxidation Induction Time (OIT) and Melt Mass Flow Rate (MFR) tests were used to characterize changes in the pipes' properties, thermal stability, and melt flow behavior after aging. The Arrhenius equation was used to create a lifetime prediction model under four different temperature conditions. This study estimates the service life of PE pipes under combined photo-oxidative and thermo-oxidative aging conditions. According to research, products produced during the thermo-oxidative and photo-oxidative aging processes of polyethylene pipes can promote secondary reactions and photo-oxygen reactions. The aging rate is 1.87 times higher than that of thermo-oxidative aging alone. The MFR decreased under combined thermo-oxidative and photo-oxidative aging compared with single thermo-oxidative aging, demonstrating impaired melt flowability of polyethylene pipes caused by aging and degradation. Based on the Arrhenius equation, a multi-factor lifetime prediction model for polyethylene pipes was created.

KEYWORDS: Polyethylene pipes; oxidation induction time; melt mass flow rate; Arrhenius equation; lifetime prediction

1 Introduction

Polyethylene pipes have been widely applied in engineering practices as they overcome the inherent limitations of conventional metal piping systems. Polyethylene pipes offer superior resistance to rapid crack propagation and construction advantages due to their flexibility. It has redefined the system integrity and long-term reliability of underground pipeline networks [1,2]. This has established its core position in fields such as gas transmission and distribution, municipal water supply and drainage, where safety and durability are paramount [3]. However, as high-molecular-weight non-metallic materials, polyethylene pipes are prone to aging when exposed to various environmental factors during service. Exposure to temperature, ultraviolet radiation, and pressure accelerates oxidative degradation reactions in polyethylene pipes, leading to aging.

This aging process is one of the primary factors affecting the material's service lifetime [4,5]. However, during the long periods of construction, maintenance, sampling, and testing, the pipes that should be buried underground and used in a dark environment need to be completely exposed to light. This seriously violates the service specification for PE pipes—designed for use in dark environments. The ultraviolet in the light will cause the polyethylene pipes to undergo degradation reactions mainly due to photo-oxidation. Moreover, the light will significantly accelerate the aging process of the pipes beyond that caused by thermal oxidation, thereby reducing their service lifetime. Therefore, UV radiation should be considered during the evaluation process to predict their service life.

During the aging process, the degradation of polyethylene primarily occurs through oxidative degradation reactions. Oxidative degradation is categorized into photo-oxidative aging and thermal-oxidative aging degradation [6,7]. Wang [8] created an Arrhenius equation-based thermal-oxidative aging life prediction model for polyethylene pipes. Srii et al. [9] used a combination of modeling and testing to examine the effects of thermo-oxidative aging on the physical properties of PE pipes. Zhao et al. [10] found that the tensile strength of polyethylene first increased and then decreased with the extension of aging time under thermal-oxidative conditions. Wang et al. [11] studied the effects of photo-oxidation, ozone, temperature, salt spray, and other factors on the color, surface morphology and mechanical properties of High Density Polyethylene (HDPE). Gardette et al. [12] examined the variations in functional group concentrations produced by photo- oxidative aging and thermal-oxidative aging. Bhuyar [13] revealed via FTIR and scanning electron microscopy tests that HDPE has better UV resistance than Low Density Polyethylene (LDPE). The addition of carbon black and UV absorbers will enhance the UV resistance of HDPE [14–16]. Nevertheless, most of the existing studies focus on either single thermo-oxidative aging or single photo-oxidative aging of polyethylene pipes, and few studies have investigated the aging and degradation behavior of PE pipes under the combined action of photo-oxidative and thermo-oxidative aging. This study employs controlled temperature, ultraviolet, and pressure conditions to accelerate the aging of polyethylene pipes. Simulate the aging conditions of in-service polyethylene pipelines. By measuring the OIT, a way for forecasting the lifetime of polyethylene pipes under multifactorial conditions is established. Prediction of polyethylene pipes' lifetime under such complex factors.

2 Experiment

2.1 Accelerated Tests

This experiment produces aged polyethylene pipes through accelerated aging tests. By controlling aging temperature, ultraviolet exposure, and pressure parameters, polyethylene pipes under various aging conditions are obtained. We evaluated the performance metrics of PE pipes and investigated how various factors—including pressure, UV radiation, and temperature—affect their aging rate. Create a model to forecast how long in-service polyethylene gas pipelines will last under the impacts of thermal-oxidative and photo-oxidative aging.

This study selected polyethylene pipes, which are currently widely used and have high sales volume, as the experimental material. To obtain PE samples aged under various thermo-oxidative conditions, we first performed thermo-oxidative aging by adjusting the aging temperature and pressure parameters. Next, we subjected the thermo-oxidatively aged specimens to photo-oxidative aging. In the end, polyethylene aging specimens exposed to both thermal-oxidative aging and photo-oxidative aging were produced.

2.1.1 Accelerated Thermo-Oxidative Aging Test

Specimen aging durations were designed in accordance with GB/T 7141, "Test Methods for Thermal Aging of Plastics," as shown in Table 1. The Arrhenius equation states that the sample's aging rate roughly

doubles for every 10°C increase in the experimental temperature. Consequently, the aging impact is more noticeable at higher temperatures. However, polyethylene materials tend to soften with the increase in temperature, and the aging mechanism may change if the temperature is too high. Therefore, the aging temperature should be lower than the Vicat softening point (120°C) of polyethylene materials. Relevant literature shows that the long-period structure of polyethylene does not change with temperature below 100°C as characterized by Small-Angle X-Ray Scattering (SAXS), while the sizes of the crystalline region, amorphous region and lamellar crystal increase significantly with temperature when the temperature exceeds 110°C [17]. Based on the above analysis, 80°C, 90°C, 100°C, and 110°C were selected as the experimental temperatures in this study. At each corresponding temperature, three pressure levels were set: no pressure (0 MPa), working pressure (0.2 MPa), and design pressure (0.4 MPa). To avoid the interference of oxygen in the pipes on the experiment by accelerating the aging process, nitrogen was introduced into the PE pipes to replace air during the test (Fig. 1).

Table 1: Polyethylene pipe thermal-oxidative aging groups and aging duration.

Pipeline	Temperature/°C	Pressure/MPa	Time/h	Time/h	Time/h	Time/h	Time/h
DN110	80	0	0	144	288	576	864
		0.2	0	144	288	576	864
		0.4	0	144	288	576	864
	90	0	0	96	192	288	384
		0.2	0	96	192	288	384
		0.4	0	96	192	288	384
	100	0	0	24	48	96	192
		0.2	0	24	48	96	192
		0.4	0	24	48	96	192
	110	0	0	8	16	32	72
		0.2	0	8	16	32	72
		0.4	0	8	16	32	72

Figure 1: Thermal-oxidation aging chamber.

2.1.2 Accelerated Photo-Oxidative Aging Test

To ensure the consistency of experimental variables, the photo-oxidative aging duration was set to be the same as the thermo-oxidative aging duration (Table 2). To facilitate the clamping of specimens in the ultraviolet aging chamber and ensure that the thermo-oxidatively aged specimens are positioned uniformly for the same aging duration. The specimens were cut into 10 mm-wide semi-circular segments and placed in an adjacent. The Norrish reaction of polyethylene requires UV radiation with a wavelength range of 260–340 nm, and other wavelength bands in natural sunlight do not participate in this reaction. The UVA-340 UV lamp has a main energy output peak at 340 nm, which is consistent with the wavelength required for the Norrish reaction. Therefore, a UVA-type ultraviolet aging test chamber with a spectral distribution peak at 340 nm was selected in this study (Fig. 2), with the irradiance set to 0.9 W/(m^2·nm). Four UVA tubes were mounted at an angle on one side to ensure uniform ultraviolet radiation exposure across all areas of the specimens, which were subjected to continuous ultraviolet irradiation.

Table 2: Polyethylene pipe photo-oxidative aging groups and aging duration.

Temperature/°C	Pressure/Mpa	Time/h	Time/h	Time/h	Time/h	Time/h
80	0	0	144	288	576	864
	0.2	0	144	288	576	864
	0.4	0	144	288	576	864
90	0	0	96	192	288	384
	0.2	0	96	192	288	384
	0.4	0	96	192	288	384
100	0	0	24	48	96	192
	0.2	0	24	48	96	192
	0.4	0	24	48	96	192
110	0	0	8	16	32	72
	0.2	0	8	16	32	72
	0.4	0	8	16	32	72

Figure 2: Photo-oxidation aging chamber.

The UV lamps used in the accelerated ultraviolet aging test have irradiation intensity and total radiant exposure far higher than those of natural sunlight, and the cumulative radiant exposure during the test was calculated by Eq. (1). The cumulative ultraviolet radiation intensity under natural conditions for ten months is 405.1 kJ/m^2. Although the irradiation intensities were different, the variation range of the material before the embrittlement point was similar [18]. Schwarzschild [19] optimized the reciprocity law. It is proposed that when the product of the ultraviolet radiation intensity and the power of the aging time is fixed, the aging effects under different radiation intensities are the same. According to the principle of energy equivalence, the relationship between the accelerated aging test and natural exposure is defined as: (Ultraviolet radiation intensity in accelerated test) × (Laboratory exposure time) = (Natural ultraviolet radiation intensity) × (Natural exposure time), as expressed in Eq. (2).

$$H = 3.6It_a, \tag{1}$$

$$Q = HSn = 3.6It_aSn, \tag{2}$$

where, Q equals to cumulative radiation energy, KJ. H equals to irradiation energy, KJ. I equals to irradiation intensity, W/ m^2. t_a equals to irradiation time, h. S equals to specimen area, m^2. n equals to number of light tubes.

2.2 Characterization

2.2.1 Oxidation Induction Time

The time required for a material to undergo autocatalytic oxidation in a pure oxygen atmosphere is known as the OIT, and it is a crucial metric for assessing the performance and level of aging of polyethylene pipelines [20]. The consumption of antioxidants in the polyethylene material and its aging state can be more quantitatively shown by measuring the OIT of polyethylene pipes. The longer the OIT, the higher the antioxidant content, and the better the material's oxidation resistance. As the antioxidant content decreases, polyethylene pipes become more susceptible to aging and degradation, and the corresponding OIT of the material also decreases accordingly.

In accordance with GB/T 19466.6-2009 "Plastics—Differential Scanning Calorimetry (DSC)—Part 6: Determination of Oxidation Induction Time (Isothermal OIT) and Oxidation Induction Temperature (Dynamic OIT)", the sample shall have an aged outer layer thickness of 1 mm and a mass of 15 ± 0.5 mg. Each group of experiments was conducted three times. Select 200°C as the maximum temperature for the experiment. Nitrogen and oxygen flow rates were set at 50 mL/min, while the heating rate was set at 20°C/min (Fig. 3).

2.2.2 Melt Mass Flow Rate

The melt mass flow rate test is a key indicator for measuring the melt flowability of thermoplastics under specific temperature and load conditions. The experimental findings describe alterations in polymer flow characteristics [21]. During the aging of polyethylene pipes, molecular-level changes such as chain scission and crosslinking occur. The breakage and crosslinking of molecular chains and side chains will directly affect the melt flow properties of polyethylene materials. Therefore, the MFR test was conducted in this study to characterize the changes in the melt flow properties of polyethylene pipes during the aging process.

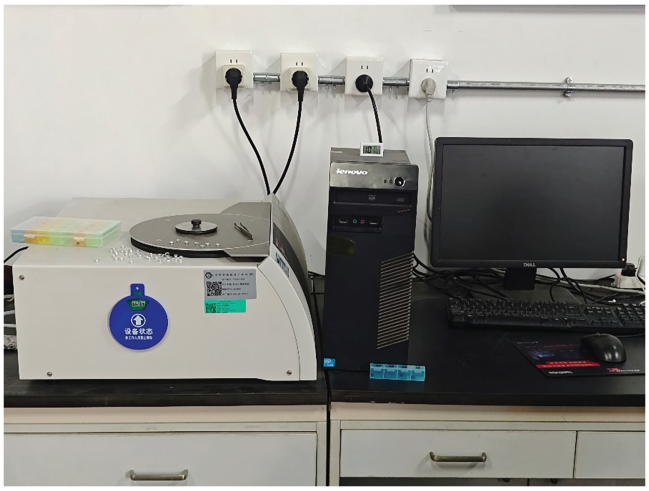

Figure 3: Differential scanning calorimeter.

After aging the polyethylene pipe specimens, conduct an MFR test in accordance with the relevant standards for polyethylene materials specified in GB/T 3682.1. The test temperature for polyethylene material is 190°C, with a load of 5 kg (Fig. 4). For PE80 material with a melt mass flow rate of 0.4–1 g/10 min, the specimen mass is 4–6 g, the extrusion cut interval is 40 s, and the cut strand length ranges from 10 to 20 mm. Make sure the specimen is small enough to fit easily into the cylinder chamber during testing.

Figure 4: Melt mass flow rate tester.

2.2.3 Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) was used to characterize the changes in the functional groups of PE pipes with aging time, which can effectively reflect the aging degree of the materials [22]. The infrared spectral changes of polyethylene pipes during aging are closely related to their internal microstructure. With the extension of aging time, the transmittance of the characteristic peaks changes significantly, indicating that the molecular structure of the samples has been damaged to varying degrees. The test parameters are as follows: the reflecting crystal is ZnSe, the incident angle is 45°, the scanning times are 32, the scanning range is 4000–500 cm^{-1}, and the resolution is 4 cm^{-1} (Fig. 5).

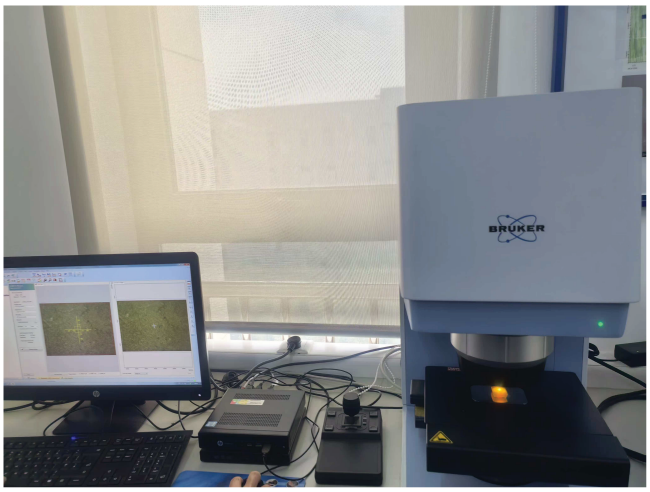

Figure 5: Fourier infrared spectroscopy tester.

3 Results and Discussion

3.1 Mechanism Analysis

The aging of polyethylene pipes is a comprehensive process caused by two main factors: on the one hand, the gradual consumption of antioxidants in the material reduces its oxidation resistance; on the other hand, oxidative reactions occur inside the material, leading to molecular chain scission and crosslinking, which further causes the degradation of material performance. The presence of antioxidants enhances the stability of polyethylene pipes and reduces the rate of oxidative degradation. Oxidation reactions constitute the degradation processes of polyethylene pipe bodies, encompassing thermal oxidation aging and photo-oxidation aging.

Thermal oxidation is an autocatalytic process driven by heat and oxygen supplied from the environment, comprising three stages: chain initiation, chain growth, and chain termination. The core reaction mechanism is as follows: heat causes polyethylene molecular chains to break, generating initial free radicals. These free radicals react with oxygen to form peroxy radicals and hydrogen peroxide. Thermal action causes hydrogen peroxide to further decompose, producing a significant number of additional free radicals. causing the reaction to accelerate sharply (chain branching), leading to the breakage and cross-linking of molecular chains [23–25].

Photo-oxidative reaction occurs when polyethylene pipes absorb ultraviolet radiation from sunlight, leading to chain scission and the generation of free radicals in the presence of oxygen. Some molecules get activated after absorbing ultraviolet. These active molecules undergo oxidation with the free radicals produced by chain breaks, resulting in hydrogen peroxide and carbonyl compounds. Carbonyl groups can

initiate the Norrish reaction upon absorption of ultraviolet in the 260–340 nm wavelength range; ultraviolet light is absorbed by hydroperoxyl radicals, which mostly break down into hydroxyl and alkoxy radicals. This accelerates photo-oxidation reactions and turns photo-oxygen aging into a self-catalyzed oxidation process [12,26,27].

3.2 Oxidation Induction Time

The OIT of polyethylene materials as a function of aging time under varied temperatures, UV exposure conditions and pressure levels is presented in Fig. 6. The OIT of polyethylene materials under thermal oxidation alone falls dramatically with temperature up to 384 h, after which the rate of decline slows. Higher temperatures accelerate the depletion of antioxidants while also triggering degradation reactions within the polyethylene material. Thermal-oxidative aging and degradation reactions cause the pipes to age. For all time periods, the OIT decreases with increasing pressure at constant temperature. It suggests that pressure can also speed the degradation of polyethylene pipe by accelerating the thermal-oxidative aging reaction.

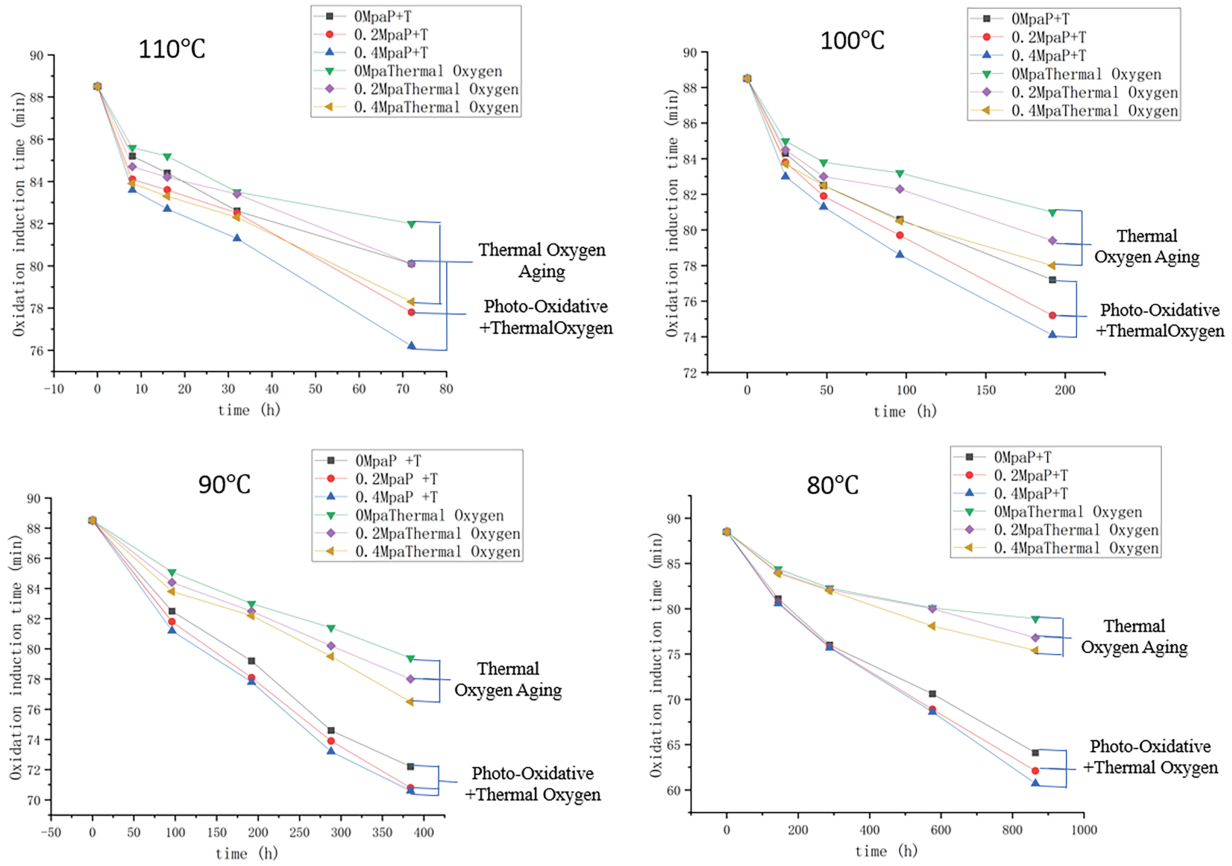

Figure 6: Relationship between oxidation induction tine and aging time at different temperatures.

Under combined UV exposure, photo-oxidative aging was insignificant during the first 48 h. With prolonged aging duration, the polyethylene pipes initiate photo-oxidative reactions, including chain scission induced by ultraviolet radiation and Norrish reactions that exclusively occur under ultraviolet conditions. Between 200 and 300 h, the rate of decrease in OIT increased significantly. Products generated from thermo-oxidative aging, in combination with UV absorption, synergistically promoted photo-oxidative reactions and accelerated the aging rate. Ultimately, the decline magnitude of oxidation induction time became

1.87 times (as expressed in Eq. (3)) greater than that under thermo-oxidative aging alone, with the OIT sharply decreasing to half its initial value (using the 20-min threshold from the standard as the failure criterion)—far exceeding the OIT loss observed in thermo-oxidative aging.

$$Multiplication\ factor = \frac{ELoss\ value}{Original\ value}, \tag{3}$$

Both thermo-oxidative and photo-oxidative degradation processes generate intermediate carbonyl compounds as by-products [28,29]. Thermo-oxidative aging consumes antioxidants within polyethylene pipes, thereby compromising the material's thermal stability. Concurrently, these carbonyl compounds absorb ultraviolet radiation, accelerating polyethylene degradation and triggering Norrish secondary reactions—processes exclusive to ultraviolet exposure conditions. The Norrish reaction causes the molecular chain to break, forming a vinyl group. As seen in Fig. 7, vinyl has the ability absorb ultraviolet light and go through reactions that lead to secondary aging of polyethylene pipes. Because of the byproducts of thermal- oxidative aging and the photo- oxidative reaction itself, polyethylene pipes are susceptible to photo-oxidative self-cycling and secondary reactions. Therefore, the combined effect of thermal- oxidative aging and photo-oxidative aging results in a faster aging rate than either method alone.

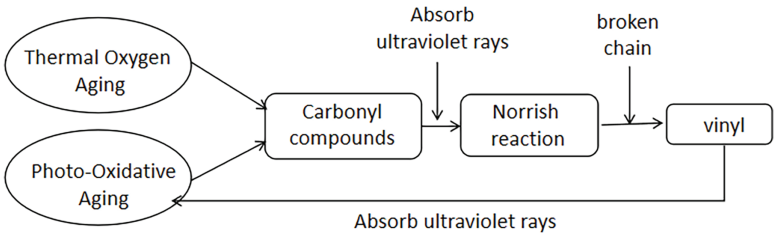

Figure 7: Schematic diagram of photo-oxidative accelerated aging.

3.3 Melt Mass Flow Rate

The results of MFR are shown in Fig. 8. At the initial stage of aging, due to the presence of antioxidants, the aging of polyethylene pipes mainly consumed the antioxidants. The results showed an alternating distribution. With the extension of time, compared with the single effect of thermal oxidation, the overall trend was a downward trend, but the range of decline was smaller. This indicates that during the aging time range of polyethylene pipes, cross-linking and chain breakage occurred simultaneously [30]. However, the rate of cross-linking reaction was greater than that of chain breakage. Therefore, the experimental results presented an alternating distribution.

3.4 Fourier Transform Infrared Spectroscopy

From the infrared spectrogram Fig. 9, it can be seen that the inherent characteristic absorption bands of polyethylene materials are -CH (2900 cm^{-1}), -CH_2 (1460 cm^{-1}), and -CH (717 cm^{-1}). Between 1500 and 1500–1690 cm^{-1} is the transmission band of carbonyl groups, indicating the presence of corresponding carbonyl functional groups. The surface of the unaged pipe has carbonyl groups because degradation inevitably occurs during the production, storage, and transportation of the pipe, resulting in carbonyl groups. As aging time increases, the absorption peak intensity increases. As aging time increases, ketone carbonyl groups undergo the Norrish II reaction under UV radiation, decomposing to form additional carbonyl groups. The degree of photo-oxidative aging gradually intensifies.

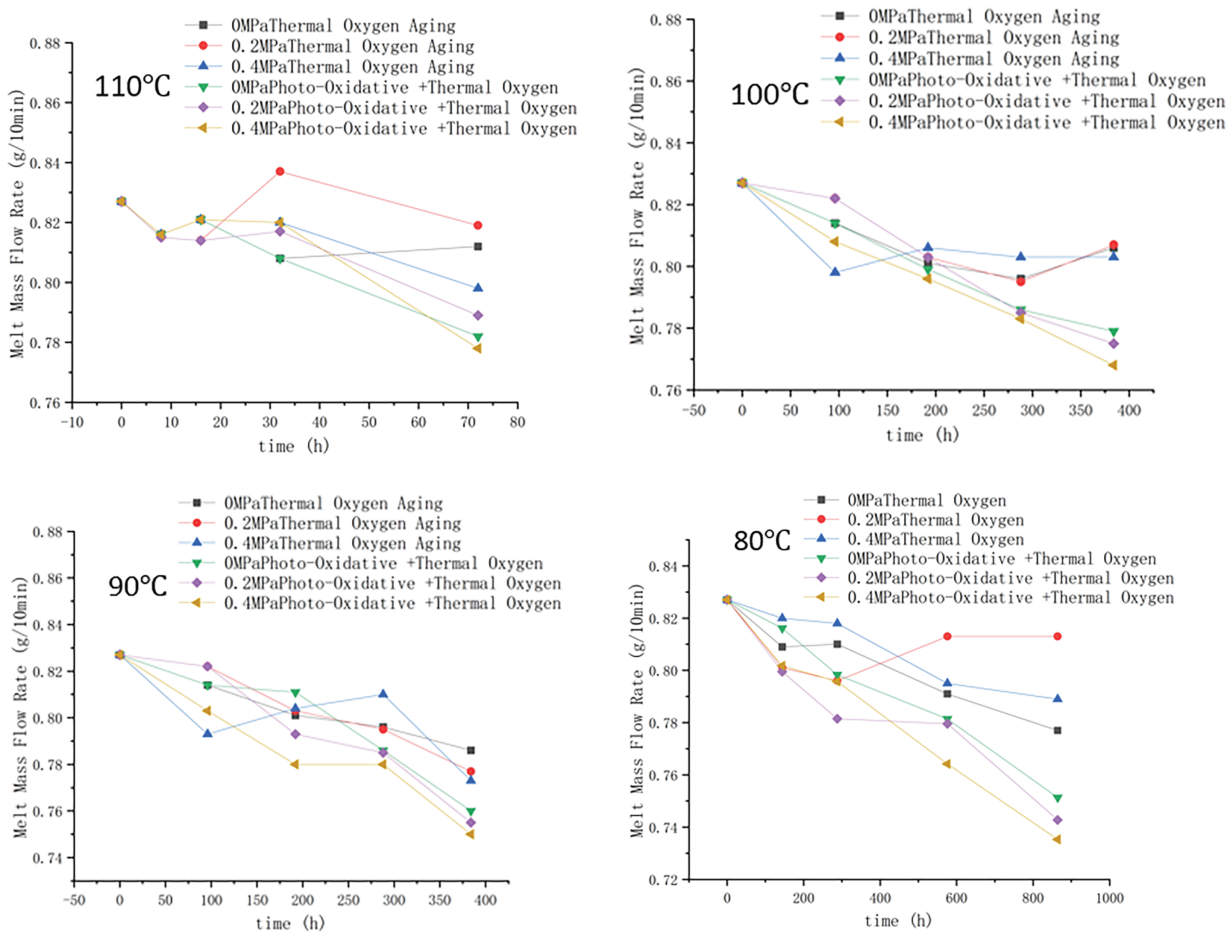

Figure 8: Relationship between MFR rate and aging time at various temperatures.

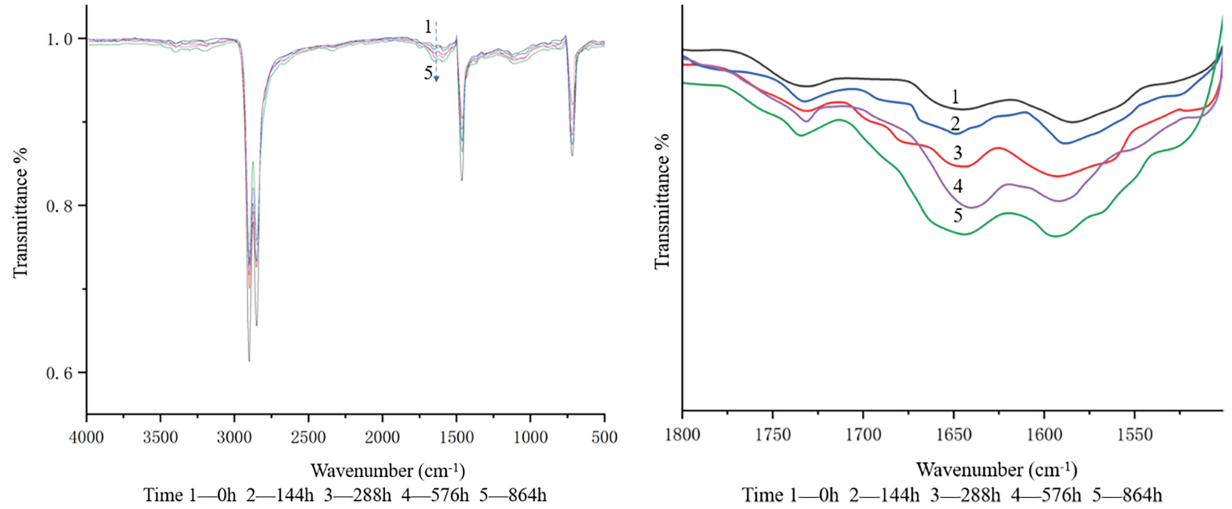

Figure 9: (**a**) FTIR curves of pipes with different ageing time; (**b**) Characteristic band analysis of oxidation products.

4 Lifetime Prediction Model

Two methods are commonly used to determine the aging rate of PE pipes: the Williams-Landel-Ferry (WLF) method [31] and the Arrhenius equation. WLF requires an operating temperature range of 30°C to 40°C, with a limited scope of application. Arrhenius requires temperatures below 30°C. The Arrhenius method is applicable at temperatures below 30°C, making it more suitable for in-service PE pipes. Thus, the Arrhenius equation is used in this study to characterize the aging rate stability [8]. Common methods for lifetime prediction using the Arrhenius equation include the linear method, the kinetic curve straightening method, and mathematical models. Linear methods require extensive calculations and can only evaluate the aging performance at specific time points. The method for linearizing dynamic curves requires minimal processing time and can calculate the aging performance of individual nodes. As a result, the dynamic curve linearization method was used for the computation.

Lifetime prediction of polyethylene pipes at different temperatures and pressures. Set 23°C as the operating temperature. According to the production standard for polyethylene pipes, the oxidation induction time at 200°C must not be less than 20 min. Therefore, an oxidation induction time of 20 min was selected as the failure threshold for the prediction model.

The kinetic curve linearization method is implemented in a two-step procedure. Firstly, the aging performance of the material is characterized according to the Arrhenius equation, and the reaction rate constant (K) at each temperature is calculated using the least squares method. Subsequently, the functional relationship with the target temperature (T) is derived based on the obtained reaction rate constants (K), as presented in Eqs. (4) and (5).

$$f(p) = A\exp(-Kt), \tag{4}$$

$$\ln P = \ln A - Kt, \tag{5}$$

where, $f(p)$ equals to the ratio of the oxidative induction time after aging to the oxidative induction time before aging. A equals to material Parameters. K equals to reaction rate constant. t equals to aging time.

Taking the logarithm of Eq. (4) and defining $x = t$, $y = \ln P$, $a_1 = \ln A$, and $b_1 = -K$, yields Eq. (6):

$$y = a_1 + b_1 x, \tag{6}$$

The coefficients a_1 and b_1, along with the correlation coefficient r, are then calculated using the least squares method.

A plot of time vs. the logarithm of OIT was constructed (Fig. 10). The fitted relationships exhibited strong linear correlations between oxidation induction time and duration across different temperatures. Subsequently, linear equations were derived via the least squares method to determine the material constant A and related parameters under various pressure and temperature conditions, as summarized in Table 3.

When the confidence level is 0.95, the correlation coefficient will decrease as the temperature rises, but it will still be greater than 0.8, indicating a good correlation. According to the standard GBT 7141-2008 "Plastic Thermal Aging Test Method", the equation considered to be satisfactory if R^2 is ≥80%. Under these conditions, the values of A are 0.97936 (0 MPa), 0.98179 (0.2 MPa), and 0.97821 (0.4 MPa).

The relationship between the reaction rate constant K and temperature T follows the Arrhenius equation, as expressed in Eq. (7):

$$K = B\exp\left[-\frac{E_0}{RT} - \frac{\alpha\frac{P_g}{P_f}}{T} + C\frac{P_g}{P_f} - \frac{D\frac{Q}{Q_0}}{T} + E\frac{Q}{Q_0}\right], \tag{7}$$

where, T equals to temperature, E_0 equals to The activation energy under standard atmospheric pressure; B maintains a constant state when the polyethylene pipe is subjected to a fixed temperature, pressure and light conditions; P_g equals to the gas pressure; P_f equals to pressure (one standard atmospheric pressure); α equals to constant; C equals to the pressure correction coefficient; Q equals to the cumulative irradiation energy; Q_0 equals to the cumulative irradiation energy under natural light; D equals to a constant; E equals to the correction coefficient for natural light and ultraviolet light. R equals to gas constant, taken as 8.314472 J/(mol·K).

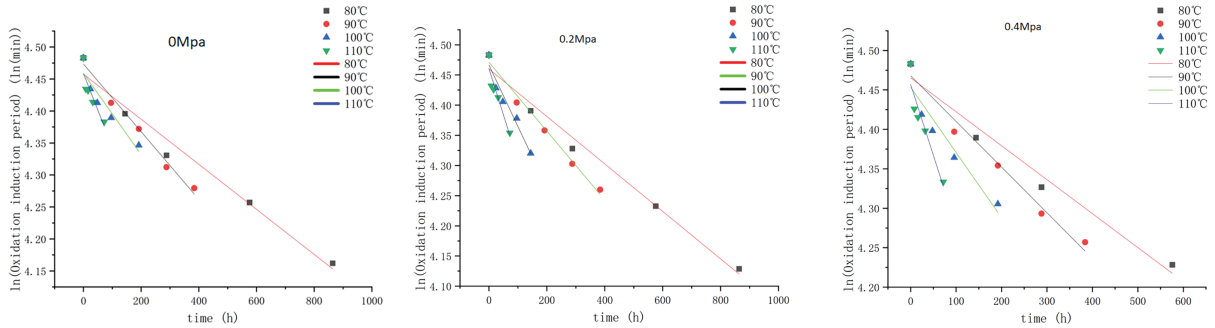

Figure 10: (**a**) The logarithmic relationship between time and the oxidation induction period at a pressure of 0 MPa; (**b**) The logarithmic relationship between time and the oxidation induction period at a pressure of 0.2 MPa; (**c**) The logarithmic relationship between time and the oxidation induction period at a pressure of 0.4 MPa.

Table 3: Statistical summary of parameters under different aging pressures and temperatures.

Temperature/°C	Pressure/MPa	a	b	R^2
0 MPa	110	4.45865	−0.00115	0.80936
	100	4.4589	−6.34452E−4	0.89647
	90	4.47343	−5.2894E−4	0.98653
	80	4.45756	−3.52217E−4	0.9755
0.2 MPa	110	4.46084	−0.00153	0.89612
	100	4.46656	−8.26443E−4	0.95211
	90	4.47114	−5.70679E−4	0.98757
	80	4.45995	−3.93436E−4	0.98532
0.4 MPa	110	4.45709	−0.00179	0.90057
	100	4.45346	−0.00102	0.91064
	90	4.46799	−5.78817E−4	0.97887
	80	4.4653	−4.30179E−4	0.97572

By setting $a_2 = \ln Z$, $b_2 = -E/R$, $x = 1/T$, and $y = \ln(K)$, and taking the logarithm of Eq. (7), (8) is obtained as:

$$lnK = a_2 + b_2 \frac{1}{T}, \tag{8}$$

A plot of ln K vs. $1/T$ was constructed to illustrate the Arrhenius relationship, as presented in Fig. 11.

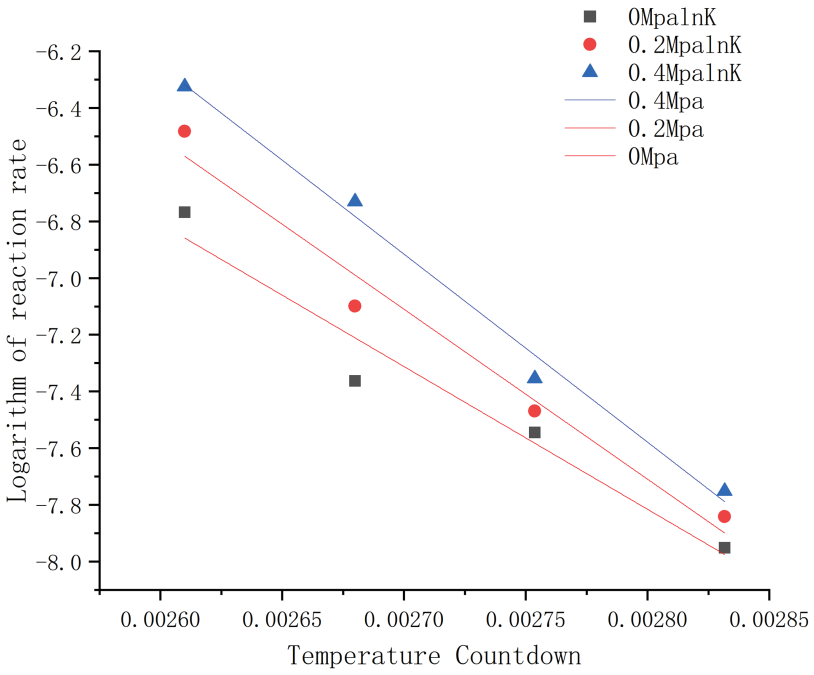

Figure 11: Arrhenius plot at different pressures.

The reaction rate and associated parameters at 23°C were obtained through linear fitting (Table 4) and subsequently substituted into the Arrhenius extrapolation formula to determine the service life of the polyethylene pipe.

Table 4: Fitting coefficient statistics.

Pressure	a1	b1	R2
0 MPa	10.98214	−6628.85377	0.99088
0.2 MPa	9.07264	−5993.53349	0.97578
0.4 MPa	6.27879	−5033.649928	0.95411

By applying the relationship $f(p) = P$ to Eqs. (4) and (9) are derived as:

$$t = \frac{1}{K} \ln\left(\frac{\overline{A}}{P}\right), \tag{9}$$

Substituting these values into the model yielded predicted service lives of 7.55 years (0.4 MPa), 11.847 years (0.2 MPa), and 14.97 years (0 MPa) for PE pipes at 31°N latitude, under ultraviolet conditions characterized by a daily radiant exposure of 1.35 kJ/m^2 at a 45° tilt angle. This study sets the maximum allowable exposure time for the entire lifespan at 2% to reduce the impact of ultraviolet rays. The test is conducted five times throughout the lifetime, with the backfilling time accounting for 1/3. Eventually, the backfilling time threshold is determined to be 88 h.

5 Conclusion

1. PE pipelines undergo significantly accelerated aging under the combined effects of photo-oxidative and thermo-oxidative aging, with the aging rate 1.87 times higher than that of thermo-oxidative aging alone.
2. The carbonyl groups generated in polyethylene pipes during thermo-oxidative and photo-oxidative aging can absorb ultraviolet radiation to promote photo-oxidative reactions and secondary reactions, and the vinyl groups produced by the secondary reactions can absorb ultraviolet radiation again to further accelerate the photo-oxidative reactions.
3. The Arrhenius equation was used to create a life prediction model for polyethylene pipes under thermal-oxidative and photo-oxygen aging circumstances.
4. Taking 31°N conditions as an example, the established lifetime prediction model indicates polyethylene pipes lifespans of 7.55 years (0.4 MPa), 11.847 years (0.2 MPa), and 14.97 years (0 MPa). Therefore, UV radiation should be considered in service life prediction. In practical construction and maintenance scenarios, pipe backfilling should be completed within 88 h to prevent accelerated aging caused by UV exposure.

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