Study on the impact of soil environment organic substances on the ageing of urban PE gas pipes in service

Manman Li
Beijing Gas Group Co Ltd Research Institute, Beijing, China
Qing Bao
Beijing Gas Group Co Ltd, Beijing, China
Sumin Lei
Beijing Gas Group Co Ltd Research Institute, Beijing, China, and
Linlin Xing and Shu Gai
Beijing Gas Group Co Ltd, Beijing, China

Abstract

Purpose – The service environment of urban polyethylene (PE) pipes has a crucial influence on their long-term safety and performance. Based on the application and structural performance analysis of PE pipe failure cases, this study aims to investigate the impact of organic substances in the soil on the aging behavior of PE pipes by designing organic solutions with different concentrations, which are based on the composition of organic substances in the soil environment, and periodic immersion tests.

Design/methodology/approach – Soil samples in the vicinity of the failed pipes were analyzed by gas chromatography-mass spectrometry, sensitive organic substances were screened and soaking solutions of different concentrations were designed. After the soaking test, the PE pipe samples were analyzed using differential scanning calorimetry, Fourier-transform infrared spectroscopy and other testing methods.

Findings – The performance difference between the outer surface and the middle of the cross section of PE pipes highlights the influence of the soil service environment on their aging. Different organic solutions can have varying impacts on the aging behavior of PE pipes when immersed. For instance, when exposed to amine organic solutions, PE pipes may have an increased weight and decreased material yield strength, although there is no reduction in their thermal or oxygen stability. On the contrary, when subjected to ether organic solutions, the surface of PE pipe specimens may be affected, leading to a reduction in material fracture elongation and a decrease in their thermal and oxygen stability. Furthermore, immersion in either amine or ether organic solutions may result in the production of hydroxyl and other aging groups on the surface of the material.

Originality/value – Understanding the potential impact of organic substances in the soil environment on the aging of PE pipe ensures the long-term performance and safety of urban PE pipe. This research approach will provide valuable insights into improving the durability and reliability of urban PE pipes in soil environments.

Keywords Urban gas pipe, Soil environment organic substances, PE pipe, Environmental aging

Paper type Research paper

1. Introduction

Polyethylene (PE) pipes are widely used in low- and medium-pressure urban gas pipeline networks because of their corrosion resistance (Khademi-Zahedi and Shishesa, 2019) and adequate mechanical strength (Wang *et al.*, 2022), meeting the current requirements. The theoretical service life of PE gas pipes is estimated to be around 50 years. However, in actual applications, gas leakage failures often occur within five to six years. Such leaks pose a direct threat to people's safety and property (Liu *et al.*, 2018). PE gas pipes are usually subjected to aging in environmental stress and soil organic media during their long-term service, leading to degradation in mechanical properties, chemical structure and antiaging performance (Liang *et al.*, 2022). Therefore, it is crucial to investigate the influence of soil organic substances on the aging behavior of PE pipes. This research laid the foundation for the study of aging behavior and the evaluation of the service life of PE gas pipes, ultimately ensuring the reliability and durability of PE pipes in gas pipeline networks.

Previous studies, such as those conducted by Frank *et al.* (2009) and Bachir-Bey and Belhaneche-Bensemra (2020), had primarily focused on investigating the changes in the aging behavior of PE pipes after 30 years of service under natural buried conditions. The PE gas pipes were only used for around 30 years in China. Consequently, research on the aging

The current issue and full text archive of this journal is available on Emerald Insight at: **https://www.emerald.com/insight/0003-5599.htm**

Anti-Corrosion Methods and Materials
© Emerald Publishing Limited [ISSN 0003-5599]
[DOI 10.1108/ACMM-11-2023-2916]

Received 13 November 2023
Revised 29 November 2023
Accepted 29 November 2023

behavior of PE pipes has mostly relied on accelerated aging tests, such as ultraviolet aging (Rodriguez *et al.*, 2020), thermo-oxidative aging (Li *et al.*, 2018) and photo-oxidative aging (Gong *et al.*, 2021). Among the various acceleration methods, thermal oxygen aging was commonly used for studying buried PE pipes. For example, Weon (2010) conducted a study on linear low-density PE pipes using thermal aging methods and found that the degree of crystallinity and cross-linking density increased while chain mobility decreased as the thermal aging time increased. This resulted in an enhancement of yield strength but a reduction in elongation at break. Chen *et al.* (2019) conducted comparative research on the thermo-oxidative aging behavior of PE pipes under cyclic and constant internal pressure. The results indicated that cyclic internal pressure promoted the breakage of molecular chains and material degradation. This led to a reduction in thermal stability because of the breakage of PE molecular chains. Although thermo-oxidative aging tests can accelerate the aging process to some extent (Celina, 2013), they do not fully consider the influence of the service environment on the performance of PE pipes. As a result, these tests may not adequately reflect the real aging behavior of PE pipes in their intended service environments.

This study collected the PE pipes and typical soil samples from the emergency maintenance worksite. The relationship between the service environment and the aging behavior of PE pipes was elucidated combining the failure cases. Gas chromatography-mass spectrometry (GC-MS) analyses of typical soil samples were performed to screen out typical and important sensitive organic substances in the soil environment. Based on the probability and proportion of organic substances and the structural properties of polymers, different concentrations of immersion solutions were designed to study the susceptibility of PE pipes against organic media to aging.

2. Experiment

2.1 Materials

1 Soil samples

Information on the soil samples was collected at the emergency repair site in the vicinity of the failed PE pipe, as is shown in Table 1.

2 Pipe specimens

The PE pipes used in the experiment are shown in Table 2.

3 Chemicals

4-Hydroxy-4-methyl-2-pentanone: industrial pure produced by Baishengjiaye (Beijing) Technology Co.

2–(2-(4-Nonylphenoxy)ethoxy)ethanol: industrial pure produced by Guangzhou Runhong Chemical Co.

2,4-Di-tert-butylphenol: industrial pure produced by Baishengjiaye (Beijing) Technology Co.

Nonylphenoxypoly(ethyleneoxy)ethanol (TX-10): industrial pure produced by Baishengjiaye (Beijing) Technology Co.

Octylamine: industrial pure produced by Baishengjiaye (Beijing) Technology Co.

Dishwashing liquid and deionized water.

2.2 Experimental methods

1 Soil organic substances analysis

- Pretreatment of soil samples

Pretreatment was carried out according to the requirements of the national industry standard HJ 834-2017. In total, 20 g of finer soil was needed, without impurities and coarsely divided by the tetrad method. After grinding, extraction, concentration, and capacity fixing, the soil concentrated liquor was obtained for testing.

- Gas chromatograph test

Inlet temperature: 280°C, no shunt; injection volume: 1.0 ul; column flow rate: 1.0 ml/min (constant flow); column temperature: start up at 35°C for 2 min and then increase up to 150°C for 5 min at the speed of 15°C/min, then to 290°C for 2.0 min at the speed of 3°C/min.

- Mass spectrometer test

Electron bombardment source (EI); ion source temperature: 230°C; ionization energy: 70 eV; interface temperature: 280°C; quadrupole temperature: 150°C; mass scan range: 35–450 u; solvent delay time: 5 min; and data acquisition mode: full scan mode.

2 Service soil environment organic substances leaching test

In total, 1 L of organic solution was required according to the concentration ratios in Table 4. The organic substances were fully dissolved and then deionized water and surfactant were added. After the solution appeared transparent and clarified, the solution was poured into a beaker. The processed tensile specimens (Figure 1) and small square specimens of 6 cm in length and 4 cm in width were immersed in the organic solution and the beaker was sealed using cling film and tinfoil. After sealing, the beakers were placed in a water bath box and immersed in a water bath at the temperature of 80°C for 21 days.

3 PE pipe performance testing

- Mechanical test methods

Table 1 Soil specimen information

No.	Status of soil samples	Years of service	No.	Status of soil samples	Years of service
GC	The soil is wet, sticky and mixed with some fine stones	5	JH	The soil is wetter, finer and mixed with some stones	10
YH	Soil is dry, fine and mixed with some larger stones	15	DL	Soil is wet, fine and mixed with some stones	20
ND	Soil is wet, fine and mixed with some stones	4	ZY	Soil is wet, fine and mixed with some stones	6

Source: Authors' own creation

Table 2 Information of PE pipe

Type	No.	Pipe grade	Outer diameter of pipe/mm	Years of service
Failed pipe	GC	PE80	110	5
New pipe	X	PE80	110	0

Source: Authors' own creation

According to the requirements of the national standard GB/T 8804.3-2003, the PE pipe was prepared. The mechanical properties of the tensile specimens were tested using an electronic universal testing machine at room temperature (23°C ± 2°C), with a loading rate of 200 mm/min, and the strain was recorded using an extensometer. Five parallel specimens were used for each type of pipe and the measurements were averaged.

- Oxidation induction time test method

A small square of 2 cm in length and 2 cm in width was intercepted from the PE pipe, and a 1-mm-thick specimen of about 15 mg was cut at the outer surface. It was divided into two along the middle line of the cross section, and a 1-mm-thick specimen of about 15 mg was cut from the center of the pipe wall at the middle cross section. The oxidation induction time (OIT) of the specimens on the outer surface, at the middle of the cross section, was tested using a differential scanning calorimeter (TA instrument). The temperature was increased to 210°C at a rate of 20°C/min under a nitrogen atmosphere (gas flow rate of 50 ml/min), held at 210°C for 3 min, switched the gas to oxygen at the same flow rate and held for 60 min and at the end of the holding period, switched the gas to nitrogen and cooled to room temperature.

- Fourier transform infrared spectroscopy test methods

A small square of 2 cm length and 2 cm width was intercepted from the PE pipe. It was divided into two along the center line of the cross section. Fourier-transform infrared (FTIR) tests were carried out using an infrared spectrometer on the outer surface and the middle cross-sectional position of the cut out small square. The test range was from 400 to 4,000 cm^{-1}, the reflecting crystal was diamond, the incidence angle was set to 45° and the number of scans was 32 with a resolution of 0.35 cm^{-1}.

3. Results and discussion

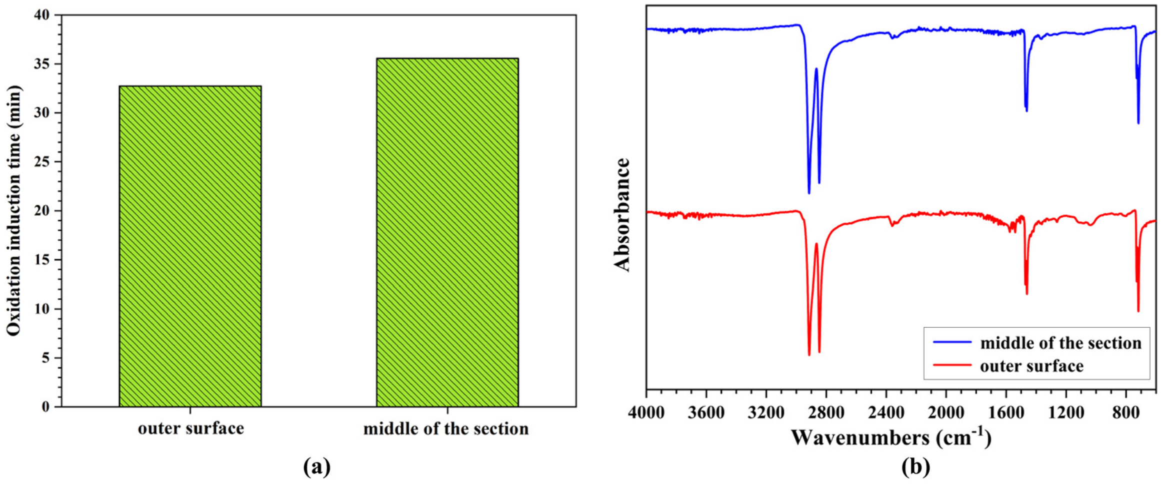
3.1 Influence of service soil environment on the structural properties of polyethylene pipes

The analysis of the performance structure of the PE pipe intercepted at the repair site can provide valuable information about the aging behavior of the pipe under service conditions. By comparing the differences between the outer surface and the center cross section, it is possible to illustrate the effect of service environment soils on the aging behavior of PE pipe.

Figure 1(a) shows that the OIT at the outer surface of the GC pipe was significantly lower than that at the middle of the cross section. Generally speaking, the OIT of each part of PE pipe in the production process is basically the same. The results indicated that the service environment indeed affects the aging process of the PE pipe after only five years of service.

To further analyze the aging failure behavior of PE pipes, Fourier infrared testing was carried out, as shown in Figure 1(b). The infrared spectrogram shows obvious infrared absorption peaks at 2,919, 2,846, 1,470 and 717 cm^{-1}, which are characteristic peaks of PE materials. The vibration peak at 2,919 cm^{-1} in the spectrogram is the antisymmetric telescopic vibration of CH_2. The vibration peak at 2,846 cm^{-1} denotes the symmetric telescopic vibration of CH_2. The vibration peak at 1,470 cm^{-1} represents the in-plane bending vibration of CH_2 and the vibration peak at 717 cm^{-1} is the in-plane rocking vibration of CH_2. It is clearly depicted that a new vibration absorption peak appeared at about 1,640 cm^{-1} on the outer surface of the PE pipe. The absorption peak here corresponds to the in-plane bending vibration of the H-O bond, indicating that a new group was generated on the outer surface of the PE pipe.

Figure 1 GC pipe



Notes: (a) OIT; (b) FTIR
Source: Authors' own creation

The presence of hydroxyl groups suggests an aging behavior on the outer surface of PE pipes.

The data emphasizes the importance of considering specific usage environments and their impact on the aging behavior of PE pipes. By comparing the performance at the outer surface and the middle of the cross section of the PE pipe, the performance deterioration of the outer surface of the PE pipe is more serious because the OIT of the outer surface is lower than that of the middle of the cross section. In general, the middle of the cross section of PE pipe is less affected by external influences, and the performance is more stable. It can be further verified that the infrared spectra at the middle of the cross section of PE pipe are equal to the typical spectra of PE materials. This indicates that the middle of the cross section was not aging in the service process. On the contrary, the outer surface of the PE pipe was in service in the soil environment for only five years, and the OIT has been reduced. Combined with the infrared spectra, new hydroxyl groups appeared on the outer surface of the PE pipe and aging occurred. The service soil environment can significantly accelerate the aging process of the outer surface of the PE pipe, leading to performance degradation and early failure. Overall, this study provides important insights into the complex aging behavior of PE pipes.

3.2 Analysis of soil organic substances in service environments

The soil medium is a complex environment that contains various substances, including metal ions, inorganic acid radical ions, inorganic matter, organic matter and more. Although PE pipes generally exhibit good resistance to corrosion from most inorganic matter in the soil environment, the presence of organic media can potentially have an impact on the performance of the PE pipe over time. Therefore, it is crucial to analyze the composition and species of organic matter present in the soil environment to better understand the aging behavior of PE pipes.

In this paper, the soil samples collected at the emergency repair site near the failed pipe were analyzed by GC-MS, and the obtained spectra are shown in Figure 2.

Based on the mass spectrometry analysis of the soil samples, it is observed that the presence and composition of organic matter in the soil environment have a significant influence on the aging behavior of PE pipes. The study found that the service life of PE pipes in environments with fewer organic media was longer. For example, in the DL soil environment where only three types of organic matter were detected, the PE pipe had served for nearly 20 years before showing signs of aging and failure. On the contrary, in the ND soil environment with a higher concentration of organic matter, the PE pipe's service life was limited to only four years This indicates that certain types of organic media present in the soil environment are particularly influential in accelerating the aging process of PE pipes. To further analyze these sensitive organic substances, the organic matter in the soil samples was categorized and divided as presented in Table 3.

The soil environment contains various types of organic matter, including alkanes, olefins, alkynes, ketone alcohols, amines, esters, ethers and phenols. While components such as alkanes, olefin, and alkynes typically do not have a significant impact on the aging behavior of PE pipes, the presence of ketone alcohols, amines, esters, ethers and phenols, which contain strong polar groups, can potentially accelerate the aging of PE pipes. These organic substances with polar functional groups may interact with the PE material. As a result, PE pipes exposed to soil environments containing ketone alcohols, amines, esters, ethers and phenols may be quickly aging and have a reduction of service life. To conduct an in-depth analysis of the impact of these specific organic substances on the aging behavior of PE pipes, it is important to further investigate their interactions with the PE material. This may involve studying the performance changes that occur when PE pipes are exposed to soil environments rich in ketone alcohols, amines, esters, ethers and phenols.

It is important to consider the combined effect of multiple organic media in the soil environment when studying the aging behavior of PE pipes. Based on the occurrence probability, the proportion of soil samples, and the interaction between organic groups, solutions with different concentrations were designed as shown in Table 4. The selection of reagents that are less hazardous and polluting further ensures the safety and environmental sustainability of the experimental approach. The use of concentration-accelerated and temperature-accelerated methods provides a means of accelerating the aging process of PE pipes in a controlled laboratory setting, allowing for more rapid testing of different scenarios and materials. The water bath temperature of 80°C is a reasonable choice for this type of experiment, as it is high enough to accelerate aging but not so extreme as to cause unrealistic or unrepresentative effects. The experimental methodology described provides a systematic approach to studying the aging behavior of PE pipes in soil environments containing multiple organic media.

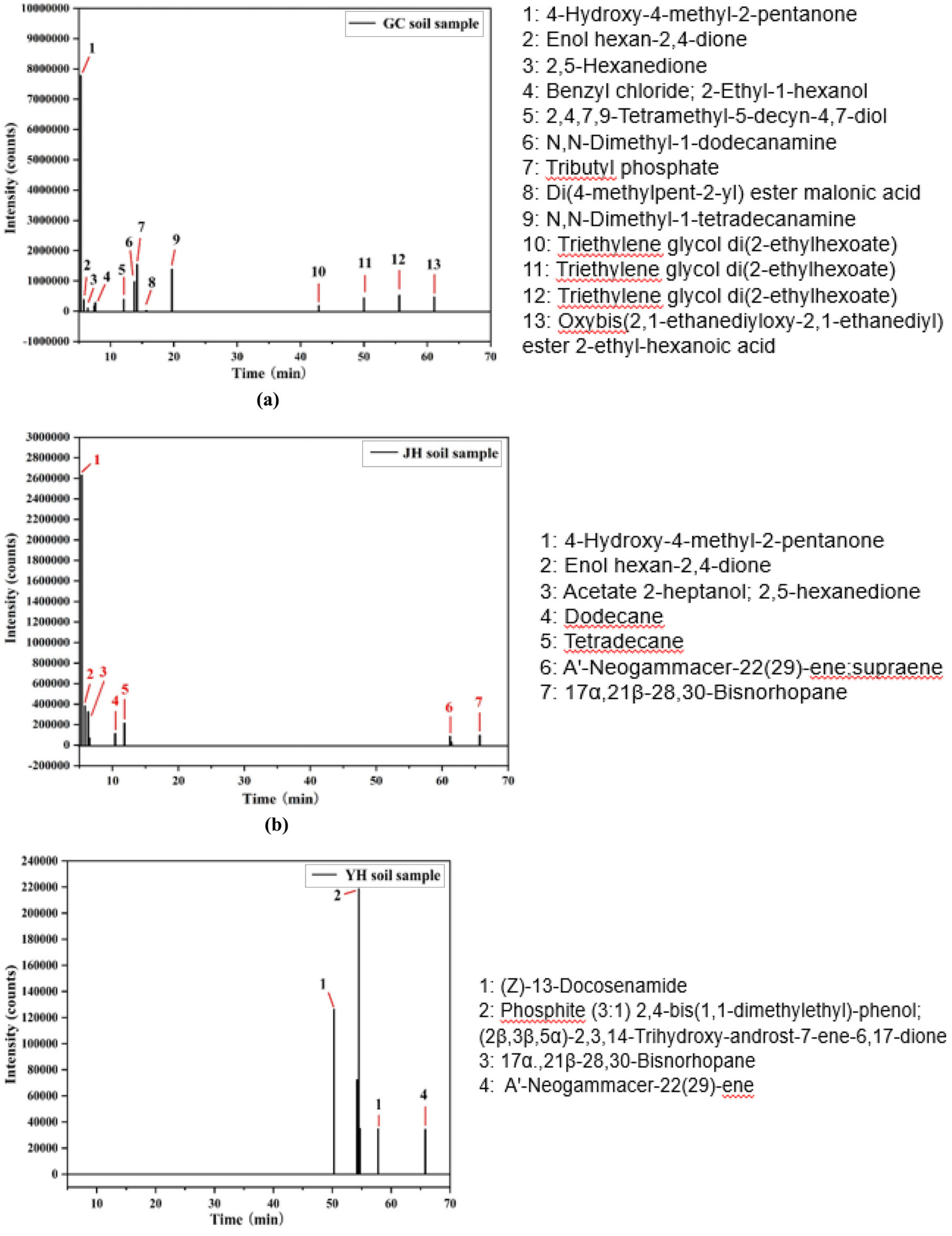
3.3 Influence of organic substances on the aging behavior of polyethylene pipes

PE pipe specimens were immersed in different concentrations of organic solutions and were weighed every three days for. After 21 days of immersion, mechanical properties, OIT and FTIR were tested. By combining these experimental evaluations, we can comprehensively assess the effects of the organic solutions on the aging behavior of PE pipes. The results obtained can contribute to a better understanding of the long-term performance of PE pipes in soil environments containing the studied organic media.

The PE pipes were weighed every 72 h, and the weight plots are shown in Figure 3. The weight was all increased in different concentrations of organic solutions as the text time increasing. Higher weight gain was observed in organic solutions with high amine content (No. 5). It is possible that the presence of amine functionalities in the organic solutions could also interact with the PE material via hydrogen bonding or other interactions, leading to more absorption. On the contrary, the lack of significant weight change in pure ether organic solution (No. 3) was notable. This suggests that the PE material may be less susceptible to absorption of nonpolar organic solvents.

Figure 4(a) shows the stress–strain curve after the mechanical tensile test, and Figure 4(b) and 4(c) shows the yield strength and elongation, respectively, at break curves. It is interesting that the organic solution with high amine content

Figure 2 Soil mass spectrometry



1: 4-Hydroxy-4-methyl-2-pentanone
2: Enol hexan-2,4-dione
3: 2,5-Hexanedione
4: Benzyl chloride; 2-Ethyl-1-hexanol
5: 2,4,7,9-Tetramethyl-5-decyn-4,7-diol
6: N,N-Dimethyl-1-dodecanamine
7: Tributyl phosphate
8: Di(4-methylpent-2-yl) ester malonic acid
9: N,N-Dimethyl-1-tetradecanamine
10: Triethylene glycol di(2-ethylhexoate)
11: Triethylene glycol di(2-ethylhexoate)
12: Triethylene glycol di(2-ethylhexoate)
13: Oxybis(2,1-ethanediyloxy-2,1-ethanediyl) ester 2-ethyl-hexanoic acid

(a)

1: 4-Hydroxy-4-methyl-2-pentanone
2: Enol hexan-2,4-dione
3: Acetate 2-heptanol; 2,5-hexanedione
4: Dodecane
5: Tetradecane
6: A'-Neogammacer-22(29)-ene;supraene
7: 17α,21β-28,30-Bisnorhopane

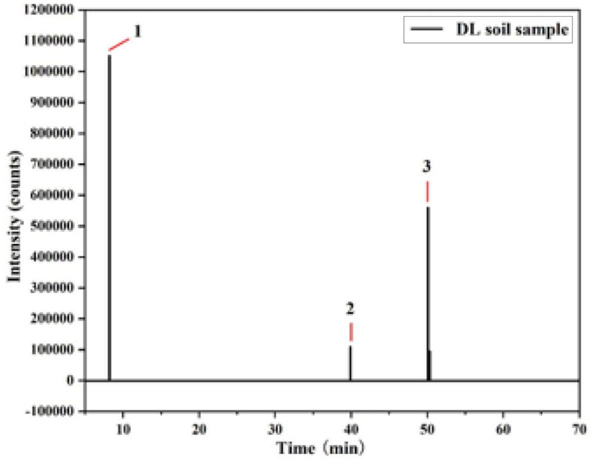
(b)

1: (Z)-13-Docosenamide
2: Phosphite (3:1) 2,4-bis(1,1-dimethylethyl)-phenol; (2β,3β,5α)-2,3,14-Trihydroxy-androst-7-ene-6,17-dione
3: 17α.,21β-28,30-Bisnorhopane
4: A'-Neogammacer-22(29)-ene

(c)

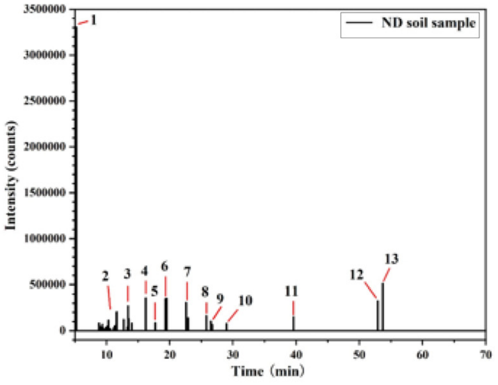
(*continued*)

Figure 2



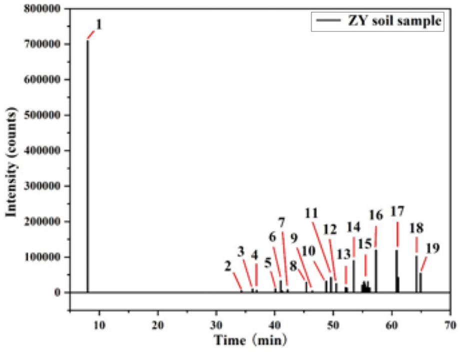
(d)

1: Benzenemethanethiol
2: (Z)-9-Octadecenamide
3: (Z)-13-Docosenamide



(e)

1: 4-Hydroxy-4-methyl-2-pentanone
2: Dodecane; 4-Methyl-undecane; 2-Methyl-undecane; 3-Methyl-undecane; Dodecane; 2,6-Dimethyl-undecane; 4-Methyl-dodecane; 2,6-Dimethyl-undecane; 4-Methyl-1-undecene; 4-Methyl-dodecane; Tetradecane; 7-Methyl-tridecane;2,7,10-Trimethyl-dodecane; Dodecane; 2,6,11-Trimethyl-dodecane; 2-Methyl-tridecane;4-Methyl-tetradecane; 2,6,10-Trimethyl-dodecane; Tetradecane
3: 2,6,10-Trimethyl-tridecane; 2-Methylt-etracosane; Pentadecane; N,N-Dimethyl-1-dodecanamine; 2,4-Di-tert-butylphenol
4: Hexadecane
5: 2,6,10-Trimethyl-pentadecane
6: Heptadecane; N,N-Dimethyl-1-tetradecanamine
7: Eicosane; 2,6,10,14-Tetramethyl-hexadecane
8: Eicosane
9: 7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione; Methyl ester hexadecanoic acid
10: Eicosane
11: (Z)-9-Octade-cenamide
12: Fluocortolone-21-pivalat
13: Tris(2,4-di-tert-butylphenyl) phosphate



(f)

1: 4-Hydroxy-4-methyl-2-pentanone
2: 3-Methyl-decane
3: Dodecane
4: 2,6-Dimethyl-undecane
5: 4,8-Dimethyl-undecane; 2,7,10-Trimethyl-dodecane
6: Dodecane;4,6,8-Trimethyl-1-nonene
7: 2,6,11-Trimethyl-dodecane
8: Tetradecane
9: Pentadecane
10: 1-Tridecene
11: Pentadecane
12: 2,4-Di-tert-butylphenol
13: 4-Tridecyl ester benzeneacetic acid; 3-Methyl-pentadecane
14: Hexadecane
15: Butylheptyl)-benzene; 1-Chloro-tetradecane; 2,6,10-Trimethyl-pentadecane; Hexadecyl octyl ether; 4-Methyl-hexadecane; 3-Tetradecyl ester benzeneacetic acid; 3-Methyl-hexadecane
16: Heptadecane
17: Hexadecane; 2,6,10,14-Tetramethyl-hexadecane
18: Eicosane
19: 7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione

Notes: (a) GC soil sample; (b) JH soil sample; (c) YH soil sample; (d) DL soil sample; (e) ND soil sample; (f) ZY soil sample

Source: Authors' own creation

Table 3 Types of organic matter in soil environment

Category	ND	ZY	GC	JH	YH	DL
Ketone alcohol	4-hydroxy-4-methyl-2-pentanone	4-hydroxy-4-methyl-2-pentanone	4-hydroxy-4-methyl-2-pentanone	4-hydroxy-4-methyl-2-pentanone	–	–
Ketones	7,9-di-tert-butyl-1-oxaspiro(4,5) deca-6,9-diene-2,8-dione	7,9-di-tert-butyl-1-oxaspiro(4,5) deca-6,9-diene-2,8-dione; 4,6, 8-trimethyl-1-nonene	2,5-hexanedione	2,5-hexanedione	$(2\beta,3\beta,5\alpha)$-2,3,14-trihydroxy-androst-7-ene-6,17-dione	–
Alcohol	–	–	2-ethyl-1-hexanol	–	–	Benzenemethanethiol
Amine	(Z)-9-octadecenamide; N,N-dimethyl-1-dodecanamine; N,N-dimethyl-1-tetradecanamine	–	N,N-dimethyl-1-dodecanamine; N,N-dimethyl-1-tetradecanamine	–	(Z)-13-docosenamide	(Z)-9-octadecenamide; (Z)-13-docosenamide
Ester	Tris(2,4-di-tert-butylphenyl) phosphate; methyl ester hexadecanoic acid	4-tridecyl ester benzeneacetic acid; 3-tetradecyl ester benzeneacetic acid	Tributyl phosphate; di(4-methylpent-2-yl) ester malonic acid; triethylene glycol di(2-ethylhexoate); oxybis(2,1-ethanediyloxy-2,1-ethanediyl) ester 2-ethyl-hexanoic acid	Acetate 2-heptanol	Phosphite (3:1) 2,4-bis(1,1-dimethylethyl)-phenol	–
Phenols	2,4-di-tert-butylphenol	2,4-di-tert-butylphenol	–	–	–	–
Ethers	–	Hexadecyl octyl ether	–	–	–	–
Alkanes	Heptadecane; tetradecane; dodecane	Dodecane; pentadecane; tetradecane.	–	Dodecane; tetradecane; 17. alfa.,21$\beta-$28,30-bisnorhopane	17.alfa.,21β-28,30-bisnorhopane	–
Olefinic	4-methyl-1-undecene	1-tridecene	–	A′-neogammacer-22 (29)-ene; supraene	A′-neogammacer-22 (29)-ene	–
Alkynes	–	–	2,4,7,9-tetramethyl-5-decyn-4,7-diol	–	–	–
Others	Hexadecyl octyl ether	–	benzyl chloride	–	–	–

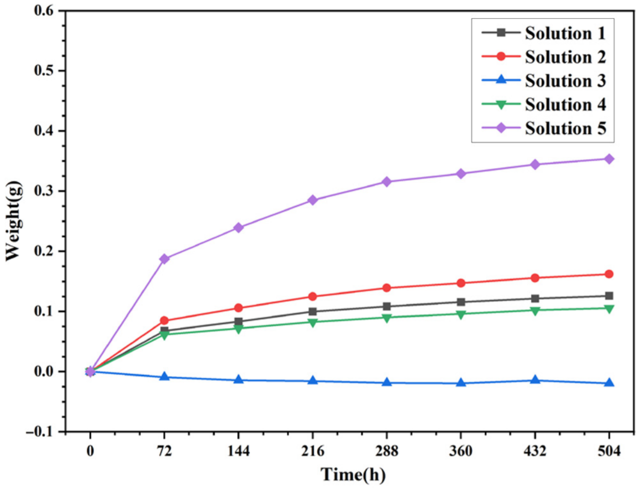
Source: Authors’ own creation

Table 4 Different ratios of organic substance concentration in environmental accelerated aging condition test

No.	Ketone alcohol (4-Hydroxy-4-methyl-2-pentanone)	Ester (2,2,4-Trimethyl-1,3-pentanediolmono (2-methylpropanoate))	Phenols (2,4-Di-tert-butylphenol)	Ethers (2-(2-(4-Nonylphenoxy) ethoxy) ethanol (TX-10))	Amines (octylamine)	Deionized water	Surfactant (dishwashing liquid)	Note
Solution 1	0.24	0.19	0.14	0.12	0.21	0.05	0.05	Composite ratio
Solution 2	0.45	0.15	0.15	0.05	0.14	0.03	0.03	ethers-less
Solution 3	0	0	0	1	0	0	0	Ether solution
Solution 4	0.36	0.19	0.15	0.2	0	0.05	0.05	Amines – free
Solution 5	0.22	0.09	0.12	0.12	0.35	0.05	0.05	Amines – strong

Source: Authors' own creation

Figure 3 Change in the weight of specimens tested in different solutions



Source: Authors' own creation

(No. 5) caused the greatest decrease in yield strength. It suggests that the amine functionalities in this organic solution may have interacted with the PE material in a way that weakened its mechanical properties. Pure ether organic solution (No. 3) caused the greatest decrease in elongation at break suggests that the PE material may be more susceptible to embrittlement or hardening when exposed to nonpolar solvents like ether. The findings suggest that prolonged exposure to certain organic solutions can lead to significant reductions in the mechanical properties of PE pipes.

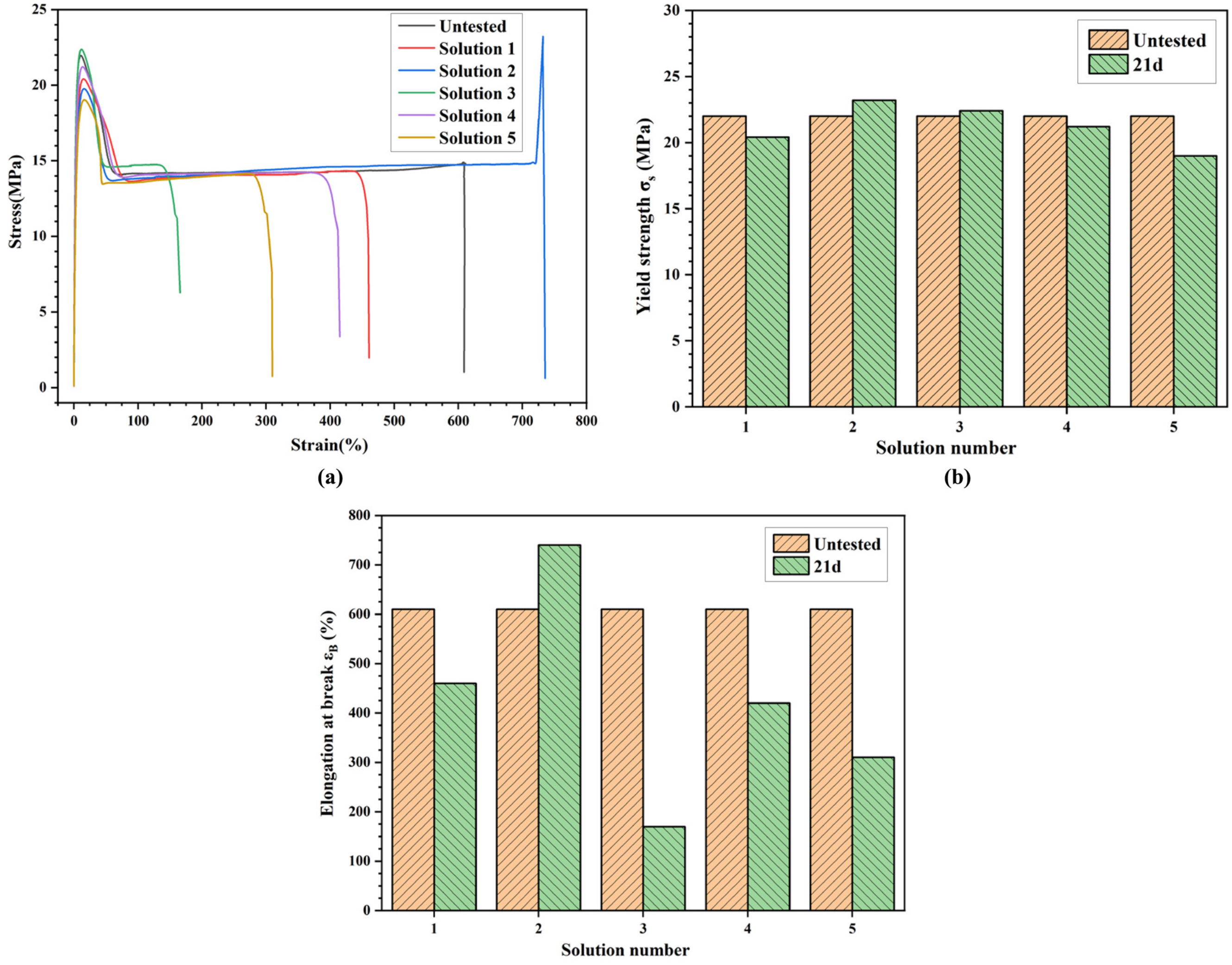
OIT is one of the important indexes to characterize the antiaging performance of PE materials. The shorter the OIT of the material, the easier the thermo-oxidative aging reaction occurs, and the thermo-oxidative stability of the material is worse. The point of switching from nitrogen to oxygen on the experimentally recorded thermal curve is labeled A1. A tangent line is drawn to the point of inflection on the thermal curve where a significant change occurs. The intersection of the tangent line with the extension of the horizontal baseline is labeled A2, and the time between points A1 and A2 is defined as the OIT of the specimen. Figure 5 shows the changes in the OIT of PE pipe specimens after 21 days of testing in different organic solutions. It is observed that the OIT of most specimens decreased to some extent after immersion in the organic solutions, suggesting that the presence of these solutions may accelerate the thermo-oxidative aging reaction in the PE material. This indicates that the thermo-oxidative stability of the material may have been compromised. It is particularly noteworthy that the OIT of the specimens was significantly shorter in the pure ether organic solution (No. 3). The pure ether solution may have had a more aggressive oxidative effect on the PE material because of its nonpolar nature and potential for promoting free radical reactions.

3.4 Sensitivity analysis of organic substances on the aging behavior of polyethylene pipes

By comparing the results of solution 1, 4 and 5, it can be found that the increase in the weight of the PE pipe specimens with the increase of amine content in the solution indicates that the organic solution containing amine organic substances can penetrate into the specimens. This penetration of organic substances can lead to changes in the original structure of the specimens, which can ultimately impact the performance of the PE pipes. The yield strength of the tensile specimens increased with the increase of amine content in the immersed organic solution, whereas the fracture elongation remained unchanged. This suggests that the penetration of amine and other organic substances altered the specimen's state and affected the interaction forces between PE pipe molecules, enhancing the activity of its chain segments. As a result, when the specimen was stretched, the molecular chain segments were more likely to move, leading to a reduction in yield strength. The unchanged fracture elongation indicates that the amine content did not significantly affect the specimen;s ability to deform before broken. As the amine content of the organic solution increases, the OIT increases. This may be due to the fact that the presence of amines in the specimen test affected the experimental test results after the amine organic substances entered the interior of the specimen. The amine organics reacted preferentially with the oxygen in the specimen, which in turn prolonged the OIT of the PE pipe.

By comparing the results for organic solutions 1, 2 and 3, it is confirmed that ether organics do not penetrate into the PE pipe specimen and only contact with the surface. However, it can still have an impact on the surface properties of the pipe and promote the expansion of defects. The decrease in the weight of the specimen when immersed in pure ether organic solution indicates that the antioxidant present in the PE pipe material is being dissolved. This can lead to a decrease in the thermo-

Figure 4 Mechanical properties of the specimens



(a)

(b)

(c)

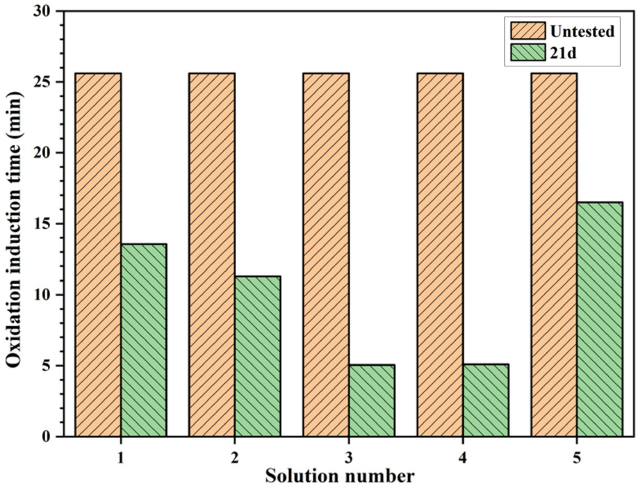
Notes: (a) Stress–strain curve; (b) yield strength; (c) elongation at break
Source: Authors' own creation

oxidative stability of the specimen and can promote the thermo-oxidative aging of PE pipe. As the ether content in the organic solution increases, the yield strength of the PE pipe specimen remains within a certain error range, indicating a more stable performance. However, the fracture elongation is significantly reduced. This phenomenon suggests that when the specimen is exposed to ether organic substances, they do not penetrate into the PE pipe specimen but promote the expansion of defects on the surface of the pipe. When an external force is applied, the specimen stretches and forms a "thin neck" region. Because of the presence of defects on the surface, the expansion of these defects is accelerated in the "thin neck" area, ultimately leading to the fracture of the specimen.

Figure 6(a) shows the infrared spectra of PE pipe specimens after surface ultrasonic cleaning in solutions 1, 4 and 5, where 0 indicates a nontested specimen. The infrared spectra showed obvious infrared absorption peaks at 2,919, 2,846, 1,470 and 717 cm^{-1}, which are characteristic peaks of PE materials. The outer surface of PE pipe specimens produced new vibrational absorption peaks at around 1,640 cm^{-1} on the spectrogram as well as at around 3,300 cm^{-1}. The infrared absorption peaks at around 1,640 cm^{-1} of the spectra indicate the in-plane bending vibration of the H-O bond, and the infrared absorption peaks at around 3,300 cm^{-1} indicate the stretching vibration of the H-O bond. The intensity of the peaks increases gradually with the increase of amine content in the organic solution. The appearance of hydroxyl groups in the spectra indicates that the aging effect has occurred on the surface of the material, and the aging degree increases with the increase of amine content in the organic solution.

Figure 6(b) shows the infrared spectra of PE pipe specimens in organic solutions 1, 2 and 3 after 21 days of experimentation. The outer surface of the specimen in the spectrogram at about 1,640 and 3,300 cm^{-1} or so have produced a new vibration absorption peaks. The appearance of hydroxyl absorption

Figure 5 Changes in the oxidation induction time of specimens after testing in different organic solutions



Source: Authors' own creation

peaks indicates that the aging effect has occurred on the surface of the material. With the increase of ether content in the organic solution, the aging of PE pipe is promoted.

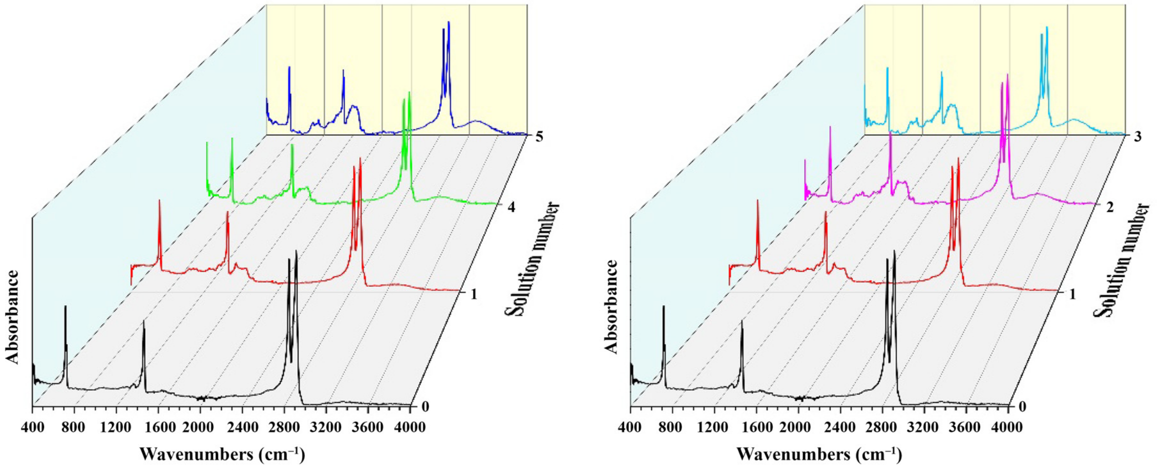
Based on the above analysis, amine organic medium has an effect on the aging performance of PE pipe. The presence of amine content promotes the aging process of the PE pipe and leads to the formation of hydroxyl groups on the material surface. In the course of experiments with PE pipes, organic substances can penetrate into the internal material. With an increase in amine content, there is enhanced infiltration, resulting in changes to the original intermolecular aggregation state and causing some degree of swelling. This swelling effect contributes to a reduction of yield strength and weakens the intermolecular interaction forces, making molecular chain segments more prone to movement. When a PE pipe is immersed in an ether organic solution, the organics do not penetrate into the interior of the material but instead act on the external surface of the pipe. These organic solutions are known to be environmental stress cracking sensitive media for PE pipes. They can promote the expansion of surface scratches, pits and other defects, ultimately accelerating the fracture of the specimen under external tension. Furthermore, ether organics can dissolve and consume the antioxidants present in the PE pipe specimens. This consumption makes the specimen more susceptible to oxidation under thermal and oxygen conditions, leading to a reduction in the oxidation resistance of the PE pipe.

4. Conclusions and outlook

The conclusions drawn from the performance analysis of the test are as follows:

- Comparing the performance at the outer surface of the PE pipe and at the middle of the cross section, the performance deterioration of the outer surface of the PE pipe is more serious, and the OIT at the outer surface is lower than that at the middle of the cross section. The difference between the internal and external structural properties reflects that the soil service environment influences the aging failure behavior of PE pipes.
- When immersed in amine or ether organic solutions, PE pipe will undergo a certain aging effect and produce hydroxyl and other aging groups on the surface of the material. When PE pipe is immersed in amine organic matter, the organic matter will penetrate into the interior of the material, increasing the weight of the pipe, reducing the yield strength of the material and enhancing the movement of molecular chain segments. When PE pipe is immersed in ether organics, the organics will not penetrate into the interior of the material. However, it will act on the external surface of PE pipe, promoting the expansion of defects such as scratches and pits on the external surface of PE pipe and accelerating the fracture of the specimen during external

Figure 6 Fourier-transform infrared spectroscopy



(a)

(b)

Notes: (a) Specimens in solutions 1, 4 and 6; (b) specimens in solutions 1, 2 and 3

Source: Authors' own creation

stretching. It can also dissolve and consume antioxidants, reducing the oxidation resistance of PE pipe.

Based on the experimental analysis, it is evident that different organic media have varying effects on the aging behavior of PE pipes. However, the specific aging mechanisms of these organic media on PE pipes have not been conclusively determined. Further clarification of the aging mechanism through microanalysis and other methods is recommended in future research.

References

Bachir-Bey, T. and Belhaneche-Bensemra, N. (2020), "Investigation of polyethylene pipeline behavior after 30 years of use in gas distribution network", *Journal of Materials Engineering and Performance*, Vol. 29 No. 10, pp. 6652-6660, doi: 10.1007/s11665-020-05118-9.

Celina, M.C. (2013), "Review of polymer oxidation and its relationship with materials performance and lifetime prediction", *Polymer Degradation and Stability*, Vol. 98 No. 12, pp. 2419-2429, doi: 10.1016/j.polymdegradstab.2013.06.024.

Chen, G.H., Yang, Y., Zhou, C.L., Zhou, Z.H. and Yan, D. (2019), "Thermal-oxidative aging performance and life prediction of polyethylene pipe under cyclic and constant internal pressure", *Journal of Applied Polymer Science*, Vol. 136 No. 28, doi: 10.1002/app.47766.

Frank, A., Pinter, G. and Lang, R.W. (2009), "Prediction of the remaining lifetime of polyethylene pipes after up to 30 years in use", *Polymer Testing*, Vol. 28 No. 7, pp. 737-745, doi: 10.1016/j.polymertesting.2009.06.004.

Gong, Y., Wang, S.H., Zhang, Z.Y., Yang, X.L., Yang, Z.G. and Yang, H.G. (2021), "The role of thermo-oxidative aging at different temperatures on the crystal structure of crosslinked polyethylene", *Polymer Degradation and Stability*, Vol. 194, doi: 10.1016/j.polymdegradstab.2021.109752.

Khademi-Zahedi, R. and Shishesa, M. (2019), "Application of a finite element method to stress distribution in buried patch repaired polyethylene gas pipes", *Underground Space*, Vol. 4 No. 1, pp. 48-58, doi: 10.1016/j.undsp.2018.05.001.

Li, H., Li, J.Y., Ma, Y.X., Yan, Q.M. and Ouyang, B.H. (2018), "The role of thermo-oxidative aging at different temperatures on the crystal structure of crosslinked polyethylene", *Journal of Materials Science: Materials in Electronics*, Vol. 29 No. 5, pp. 3696-3703, doi: 10.1007/s10854-017-8301-8.

Liang, X.B., Ma, W.F., Ren, J.J., Dang, W., Wang, K., Nie, H. L., Cao, J. and Yao, T. (2022), "An integrated risk assessment methodology based on fuzzy TOPSIS and cloud inference for urban polyethylene gas pipelines", *Journal of Cleaner Production*, Vol. 376, doi: 10.1016/j.jclepro.2022.134332.

Liu, X.B., Zhang, H., Xia, M.Y., Wu, K., Chen, Y.F., Zheng, Q. and Li, J. (2018), "Mechanical response of buried polyethylene pipelines under excavation load during pavement construction", *Engineering Failure Analysis*, Vol. 90, pp. 355-370, doi: 10.1016/j.engfailanal.2018.03.027.

Rodriguez, A.K., Mansoor, B., Ayoub, G., Colin, X. and Benzerga, A.A. (2020), "Effect of UV-aging on the mechanical and fracture behavior of low density polyethylene", *Polymer Degradation and Stability*, Vol. 180, doi: 10.1016/j.polymdegradstab.2020.109185.

Wang, M., Yang, F., Xiang, M., Yang, F. and Wu, T. (2022), "Design of molecular structure for commercial polyethylene100 pipe", *Journal of Polymer Research*, Vol. 29 No. 3, p. 84, doi: 10.1007/s10965-022-02888-9.

Weon, J.I. (2010), "Effects of thermal ageing on mechanical and thermal behaviors of linear low density polyethylene pipe", *Polymer Degradation and Stability*, Vol. 95 No. 1, pp. 14-20, doi: 10.1016/j.polymdegradstab.2009.10.016.

Corresponding author

Manman Li can be contacted at: 363902379@qq.com