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Review

Failure and fracture in polyethylene pipes: Overview, prediction methods, and challenges

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ABSTRACT

Due to the superior properties of polyethylene (PE) pipes, their applications covered a broad range of urban and engineering demands. Currently, one of the crucial issues in highly developed pipe line systems is the life and failure prediction in distribution network. Since PE pipes have been employed in gas transmission systems, the safety issue has been considered precisely. This aspect is directly related to the service life and occurrence of failures on the PE pipes. In this research, we comprehensively reviewed previous studies and investigations which have been carried out to predict the life time or mechanical failures in different PE pipes. The existing works are analyzed and discussed in details concerning the mechanical tests, artificial intelligence approaches, failure rates and time to failure in PE pipes. The aim of the present study is to classify and analyze the obtained results from previous researches to describe details of the employed techniques, tests, and models in this field. Analysis and discussion presented in this review, indicates advantages, limitations and research gaps in this area. Finally, perspectives and future research directions are presented.

1. Introduction

Pipes are significantly important in transportation of gas and liquids, particularly natural gas, water, and oil. Long-distance pipelines are quite significant from a geopolitical perspective. For example, in the Caspian Sea region, construction of pipelines play a crucial role for oil export. In the past few decades, pipelines are considered as one of the most efficient and affordable methods for transportation of oil and gas. Compared to the ground or rail-bound transportation, the pipeline continues to be the least expensive option for transcontinental transportation [1]. Since pipeline installations are significantly increased in the current century, failure problems in the pipelines have been drastically increased. Therefore, study the failure of pipeline is a necessity to reduce serious injuries and financial losses.

In industrial structures such as oil and gas pipelines, the presence of cracks at a critical load can lead to total destruction. In this context, fracture mechanics is beneficial in study of macroscopic defect damage. In addition, a review of literature indicates that the finite element model (FEM) and artificial intelligence (AI) approaches are employed to study failures in the pressurized structures over the years [2–5]. For instance, an extant study [6] deals with failure rate prediction by neural network in the water pipe network. It was concluded that including further input signals (e.g., street or pipe-depth laying) can improve the model. Later, in [7] AI was used to categorize different failures in the gas pipelines.

The review of existing literature reveals that the several materials have been used for construction of the pipelines over the years and the cast iron is the first material was used. In details, the rigid iron pipes were produced using three basic techniques, each of

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which improved on the previous one: horizontal pit casting, centrifugal spinning, and vertical pit casting (cast iron). Later, ductile iron and steel were introduced as alternatives to iron pipes [8]. Steel is more ductile and stronger compared with the cast iron, but it has a lower resistance to corrosion and tensile strength. Therefore, more maintenance is required which can be considered as a disadvantage, but steel costs less than ductile iron and its welded joints show number of benefits in high pressure pipes [9]. Polyvinyl chloride (PVC) was first developed in the latter half of the 1950s and provided a flexible and an alternative to steel that resists corrosion. Due to the advances in manufacturing process, application of PVC has rapidly increased over the last decade [10]. In the 1980s, PVC and polyethylene (PE) were two of the most widely used forms of plastic pipes. PE remains the material of choice today, because of its favorable properties, such as high flexibility, outstanding resistance against corrosion, and simple maintenance. According to a report from U.S Department of Transportation [11], PE is the primary material used in the construction of gas pipeline systems. Additionally, based on Plastic Pipe Database Committee [12] more than 90% of the gas pipeline in Europe and the majority (95%) of the plastic pipes in the US are made of PE pipes. Considering applications of PE pipes, failure in these pipes can lead to leakage, explosion, and serious consequences. Therefore, failure in PE pipelines and lifetime prediction of PE pipes are crucial issues for the manufacturers and pipe operators.

Literature investigation confirmed that several experimental and numerical studies have been performed to analyze the failure in PE pipes [13–15]. For instance, in [16] a phenomenological approach by combining experimental practice and FE simulation was proposed to simulate ductile fracture and large deformation of PE pipes. The results of FE simulation are used to characterize damage evolution rate's impact on the load-stroke curve. Later, a new method was recommended to predict the lifetime of natural gas PE pipes [17]. In this context, chemical analysis for oxidative induction time and air pressure testing were combined to predict the lifetime of PE pipes. It was concluded that the oxidative induction time decreased with the increase of pressure, which confirmed that the properties of PE pipes were affected by pressure. In a study [18], crack growth behavior in high-density PE pipe was investigated. Particularly, the stress intensity factor was kept constant within a predetermined crack length range. The obtained results indicated that in the defected pipe, crack and process zone growth resistance values were noticeably low compared with a normal pipe.

In the present study, failure behavior and fracture of PE pipes have been reviewed based on an extensive literature review of articles indexed in scientific databases. The aim of this review is to gather, categorize, and analyze information on the failure and lifetime prediction of PE pipes. Therefore, we outline failure mechanisms of PE pipes, which should be considered for further developments. To this end, the remainder of this paper is organized as follows: in the next section the details of the review methodology are described. Section 3, presents a brief overview of failure mechanisms in PE pipes. In Section 4, failure and prediction of the lifetime in PE pipelines are comprehensively reviewed. In Section 5, current challenges and prospects are explained. Finally, a conclusion has been furnished in Section 6.

2. Review methodology and structure of the paper

The following research questions are attempted to be answered by this review: (i) Which solutions have been shown to be effective for failure prediction in PE pipes, and what are their benefits and drawbacks? and (ii) How the researches deal with the challenges in the field of failure in PE pipes and which limits and subjects are currently being developed?

To address the aforementioned issues, a systematic literature review has been conducted with an emphasis on the papers published in the current century. In this context, different literature searches were performed for two aspects of failure in PE pipes and prediction of failure and lifetime of PE pipes. The details of the search and selection method are outlined as follows: the published scientific works in different libraries and databases, including ScienceDirect, Scopus, SpringerLink, ASME digital collection, ASCE, ACM digital library, PubMed, and Wiley online library have been reviewed. The adopted keywords for the searching include but are not limited to "Failure in PE pipes", "Polyethylene pipes", "Failure prediction in PE pipes", "lifetime of PE pipes", "Failure analysis in PE pipes", "Fracture in PE pipes" and their combinations. The search had led to over 195 documents, which were further filtered considering the keywords and the content. Later, titles, abstracts, and keywords were extracted as shown in Fig. 1. The papers that were not pertinent to this study were eliminated from the search results, and the extant peer-reviewed original investigations written in the English language were chosen to review in this study. Moreover, the selected research studies have also been examined to identify research gaps, challenges, and potential future study areas.

3. A brief overview of failure in PE pipes

The safety of the pipelines depend on the material properties (e.g., tensile strength and fracture toughness), size and geometry, and loading conditions. Based on the environmental conditions and the loading spectrum, failure modes in PE pipes under inner pressure are classified into three modes: ductile failure, quasi-brittle failure, and the brittle failure as illustrated in Fig. 2. The creep expansion in PE pipe at a high inner pressure causes the ductile failure. The quasi-brittle failure is characterized by the crack growth at a slow rate [19]. The brittle failure is the last failure mode which often occurs under a lower stress level compared to the ductile failure.

The brittle failure of PE pipes indicates a comparatively lengthy lifetime compared to the ductile failure, which denotes a short lifetime. As discussed in [20], the minimum lifespan of PE pipes is set at fifty years and a long time is required for the transition from ductile failure to brittle. In transition from ductile to brittle failure, the slow crack growth (SCG) is the key factor in failure of PE pipes which is the major reason of the ultimate failure [21]. The rapid crack propagation (RCP) represents the crack grows at a

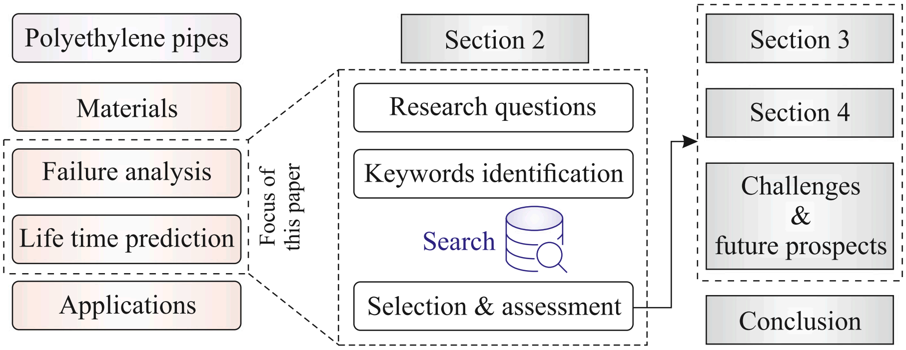

Fig. 1. Review methodology and structure of the paper.

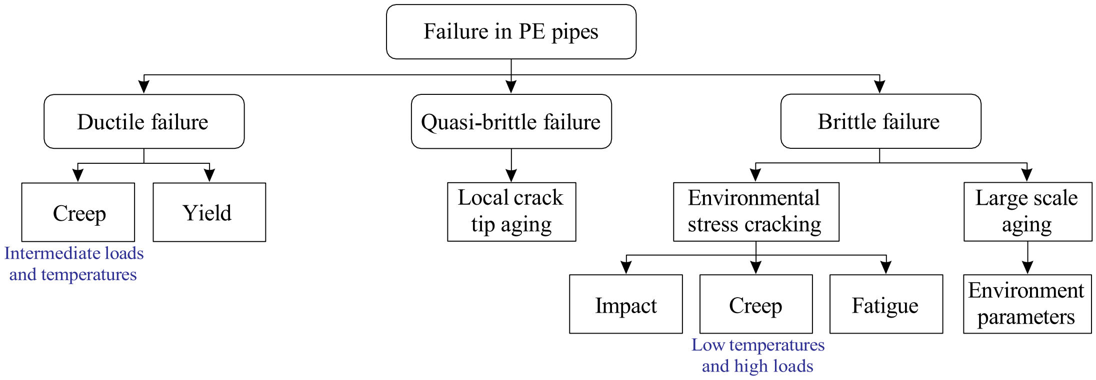

Fig. 2. Classification of the failure in PE pipes depending on the loading and environmental conditions.

rate of a few hundred meters per second [22]. When there is an accidental crack in a pipe, the RCP model indicates how the crack spreads quickly.

There are several parameters which should be considered as pipe intrinsic factors influencing PE pipe failure. Five main factors are as follows:

- Joint systems: PE pipes can be assembled into the pipeline networks by means of mechanical assembly techniques or heat fusion. Each method offer its particular advantages and limitations that user may encounter. The quality of the joint has a significant effect on the lifetime of the pipeline networks [23], therefore, joining PE pipes is considered as a crucial parameter in PE pipe failure.

- Manufacturing defects: Failure of the PE pipe is more likely to occur when manufacturing defects are introduced. Manufacturing defects can eventually lead to failure, because they cause micro-cracks and porosity issues. Moreover, residual stresses can lead to failure in PE pipes, which are results of the cooling phase in the manufacturing process [24].

- Damage in handling and storage: Poor pipe handling can lead to invisible cracks in PE pipes. Moreover, installation problems occur due to the poor storage and pipe assemblies. Unprotected outdoor storage and ultraviolet radiation for long periods of time affects PE pipes [25], thus, ultraviolet stabilization package must be used in fabrication of PE pipes.

- Pipe age: As discussed in [26], pipe age have a linear relationship with failure rates, and this relationship is more complex in older pipes. The failure rates are likely to increase with increasing pipe age. Indeed, the failure was found to increase with time after installation.

- Chemical degradation: Pipe wall thinning caused by chemical deterioration affects the material integrity of the pipes. An extant study [27], examined degradation in PE pipes when fluids were conveyed through them which frequently alter internal pipe wall structure. Although PE pipes are resilient to corrosion, they are susceptible to organic compounds found in chlorinated water and contaminated soil.

It is noteworthy that the failure in different PE pipes is not limited to the above-mentioned intrinsic factors. There are other issues such as excavation load [28], pipe diameter [29], and traffic load [30] which play important roles in failure and rupture of PE pipes. Although there are different mechanisms for crack propagation in ductile and brittle failures, in both cases, cracks typically start on the pipe surface [31,32]. In fact, the same pipe can show brittle or ductile failure depending on the pressure and temperature utilized during exploitation. When a PE pipe experiences a mix of an environmental agent and a stress field, the environmental stress cracking (ESC) would occur. Interaction between parameters in ESC of PE pipes is illustrated in Fig. 3. There are several similarities between SCG and ESC, including temperature, brittle-like failure surface, and load dependency of the failure time. However, there is SCG if the surrounding medium does not affect the failure mechanism, but when the medium has a significant effect on the failure,

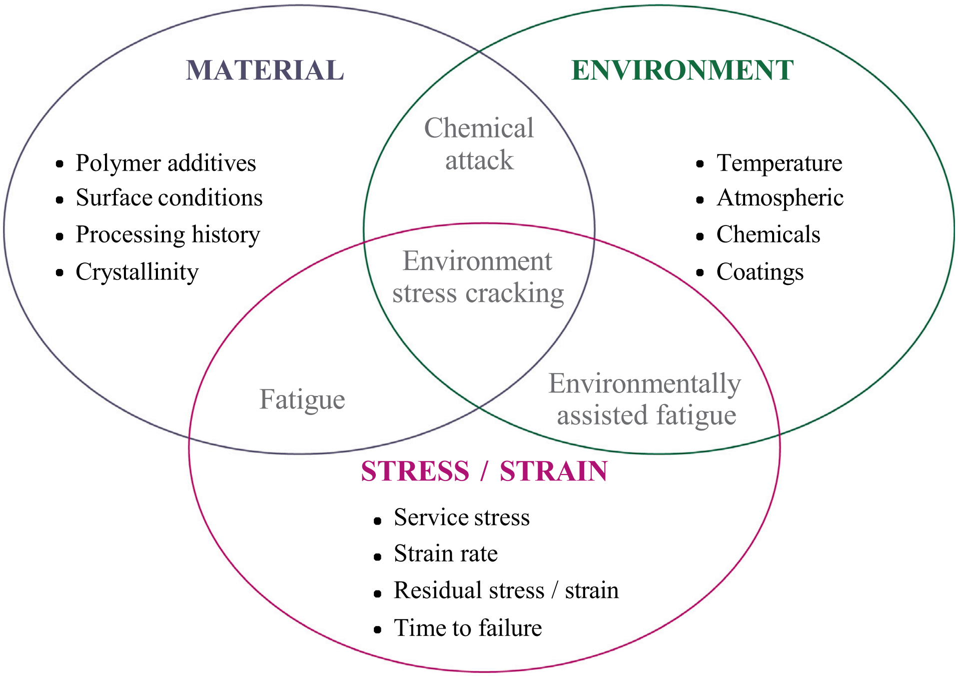

Fig. 3. The interaction of environmental factors, material integrity, and stress–strain relationship in environmental stress cracking of PE pipes.

ESC should be considered. The simultaneous action of fluidic medium and stress/strain leads to ESC. Crazing (stress cracking) is the result of ESC in PE material, which is due to the chemicals cations in a stressed material. As discussed in [33,34], crack initiation and SCG strongly depend on molecular structure and the morphology of material. Therefore, a significant increase in the resistance to crack initiation can be obtained by an improve in the polymerization process.

Currently, ESC is used as a method to assess the long-term performance of PE material [35–37]. Although PE pipes have been successfully used in various industries, identifying a comprehensive relationship between all parameters and different failure modes is yet to emerge. In the following section, we present a review on different failures in PE pipes and lifetime estimation techniques. This data can help understanding details of failure and performance of PE pipes and also improve the modeling approaches.

4. Failure and lifetime prediction in PE pipes

In this section, the main failure modes of PE pipes have been reviewed. Moreover, the mechanical and chemical lifetime are considered and the lifetime prediction methods have been outlined.

4.1. Failure in PE pipes

As previously mentioned, according to extensive researches [38–41], the failure behavior of PE pipes consists of three stages (see Fig. 4).

In the ductile failure (stage I), the failure is occurred at high stress levels by ductile deformation with large plastic zones. When the PE pipe is exposed to high stresses that are close to its elastic capacity, the ductile failure mode occurs. The semicrystalline character of the material has an impact on the ductile performance of PE under tensile load.

The failure mechanism shifts to quasi-brittle failure (stage II) at the lower loading, where SCG failures occur over a long period of time. The time to crack initiation differ between 20% to 80% of the overall lifetime [42], and it is challenging to identify the mechanical knee.

In the brittle failure (stage III), the failure time is essentially unaffected by the stress being applied. The transition from quasi-brittle failure to the brittle failure is known as the chemical knee. The main causes of the brittle failure are polymer degradation, aging processes, and stress corrosion cracking. A sufficient amount of carbon black or additives (e.g., UV stabilizers and antioxidants) can help to increase the pipe lifetime and prevent this stage before the expected lifetime [43].

Although macroscopic yielding is associated with ductile failure in PE pipes, the brittle failure is linked to the crack growth. In fact, the mechanism of ductile failure is connected to viscoelastic behavior of PE material. The faster process determines the final failure under given stress, temperature, and notch depth. The brittle behavior has been noticed at both high and low speeds, but a characteristic of ductile failure is intermediate speed.

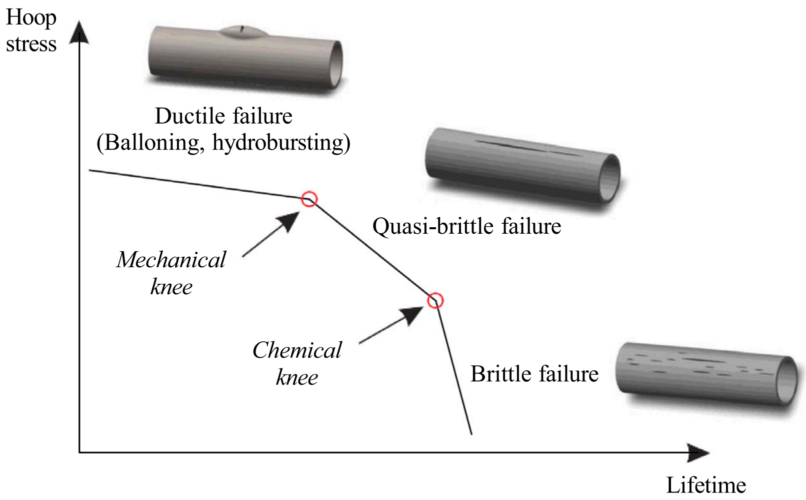

Fig. 4. A schematic of different failure modes in PE pipes.
Source: Adapted from [44].

Table 1
Different test methods to investigate long-term behavior of PE pipes.

Test method	Advantages	Disadvantages	Ref.
Creep rupture strength (Stage I)			
HDB	Test on full scale pipe	Test duration: 10 000 h	[51]
TTS	Simple test procedure	Requires many specimens	[52]
DMA	Easy to analyze the results	The formation is limited	[53]
SIM	Relatively short test	Difficult to analyze the results	[54]
SSM	Relatively short test	Adjusting the fitting parameters	[55]
Resistance to stress cracking (Stage II)			
ESCR	Different environments	Large standard deviation	[56]
PENT	Flexible test	Relatively long test	[57]
NCLS	Relatively short test	Very aggressive environment	[58]
UCLS	Recycled PE can be used	–	[59]
Long-term oxidation (Stage III)			
OIT_{Time}	More sensitive	Not good for long-term evaluation	[60]
$OIT_{Temp.}$	Low standard deviations	Unsuitable for different polymer	[61]

The failure mechanism in quasi-brittle failure can be explained with linear elastic fracture mechanics (LEFM) concepts. By investigations on the previous studies, it is found that in studies of PE pipes a lot of attention had been paid on the RCP and SCG. The small-scale steady-state test and full scale test are two methods to evaluate PE pipes' resistance to RCP. The latter method is also known as S4 test which is aimed to study propagation of a crack in a PE pipe at a specified temperature and internal pressure [45]. Determining resistance of PE pipes to SCG is based on the hydrostatic rupture test which is required to performed on the full-sized samples at different stress levels and temperatures. In order to avoid lengthy hydrostatic rupture test, several laboratory test procedures have been developed. These methods are Notched Constant Load Test (ASTM F2136 [46]), Pennsylvania Notched Test (ASTM F1473 [47]), Bent Strip Test (ASTM D1693 [48]), Full Notch Creep Test (ISO16770 [49]), and Notched Pipe Test (ISO 13479 [50]). Each stage of PE pipe failure has a different test technique and each test has certain benefits and drawbacks. These test methods are summarized in Table 1.

Amorphous polymer chains and lamellar crystal make up microstructure of PE at the microscopic level. In failure of PE material, the polymer chain connected crystalline regions-tie molecules and amorphous which have the biggest influence. Under a high stress, the tie molecules are stretched until they are unable to withstand the imposed force. Therefore, the lamellar crystal fragments into smaller pieces and the ductile failure takes place [62].

The ductile failure of PE pipe on the macro scale is characterized by a significant yield of material near to damaged area, and it typically takes place under higher stress levels in a short time. The ductile failure is linked to the viscoelastic behavior of PE materials. Particularly, with respect to the creep fracture, where the creep rate determines when ductile failure occurs.

Researchers in [63] fabricated PE pipes under different extrusion rates and temperatures. Later, all PE pipes were subjected to hydrostatic experiment to determine effects of process parameters. All pipes failed in a ductile fashion with a localized ballooning which was clearly visible prior to the failure. As discussed in [64], the ductile failure might occur in response to other significant external load, like mechanical excavation and third-party damage. The ductile failure due to the mechanical excavation is discussed

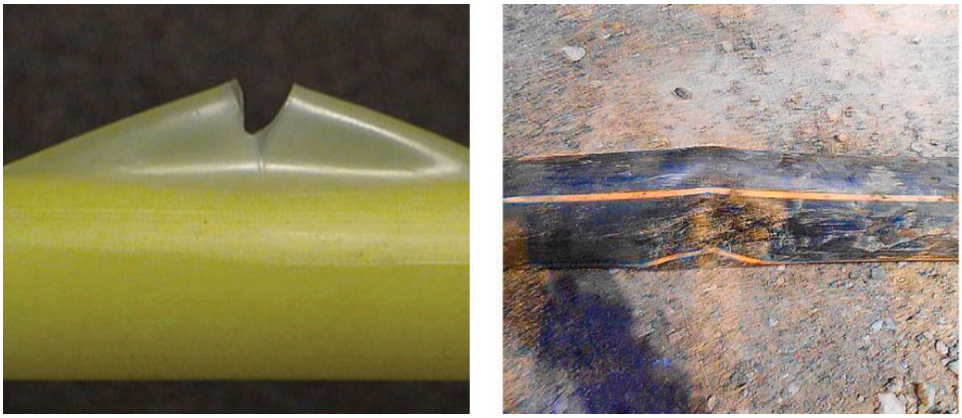

Fig. 5. The ductile failure in PE pipes; due to hydrostatic test (left) [63], and mechanical excavation (right) [65].

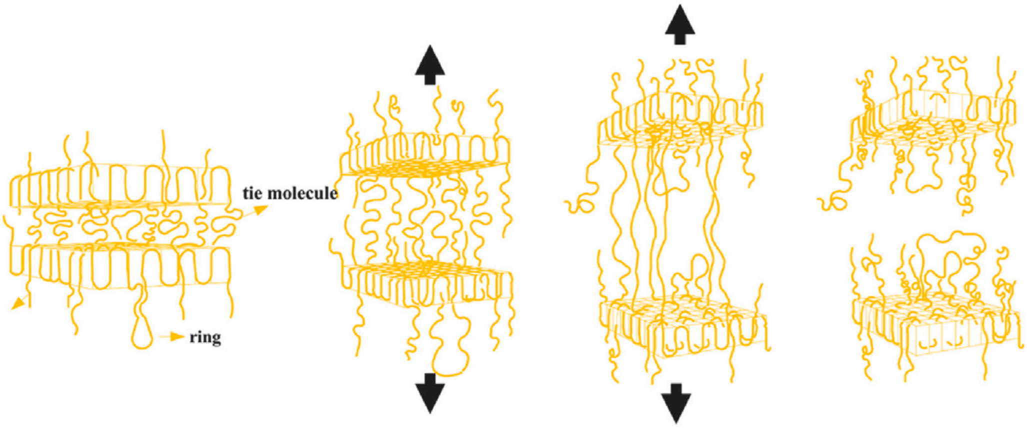

Fig. 6. The microscopic brittle failure in PE pipe [74].

in [65]. In this respect, influence of different parameters such as diameter, pipe wall thickness, internal pressure, and excavation position were determined. In Fig. 5, the ductile failures due to the hydrostatic test and mechanical excavation are illustrated. It is noteworthy that a number of authors [66–68] have recognized that there are different types of external loads (e.g., ground movement) which leads to high stresses and finally ductile failure in the pipes.

In PE materials, the brittle failure frequently occurs at the lower stress levels than ductile failure. The tie molecules would be relaxed over the time at the microscopic level, therefore, some of them pulled put from the crystalline area gradually (see Fig. 6). The stress concentration increased in the few remaining tie molecules, and by continuous pulling out of tie molecules the cracks would be extended and the brittle failure takes place [69–71]. In fact, if the mechanical force is not enough to plastically deform polymer crystallites, tie molecules begin to detangle, which often leads to brittle failure. Thus, brittle failure can be considered as a rate-dependent process. In fact, brittle failure is caused by low loading conditions and a long time which allows molecular disentanglement. In PE material with a high proportion of tie molecules compared to crystalline molecules, there is a high ductility, but there is a low stiffness. However, the amount of tie molecules is influenced by different parameters, such as processing, molecular size, and distribution. One efficient way to increase resistance to SCG is to form short chain branches along the longest molecules in the molecular weight distribution. This issue demonstrates the crucial influence of inter-lamellar tie molecules on SCG resistance. Although large local strain can be observed after ductile failure, the plastic strain is hardly visible in the brittle failure. In a similar study [72], the brittle failure mode was observed in cracked specimen of PE pipes. It is noteworthy that the rate of crack initiation and propagation is frequently correlated with the density of a physical network that is created in the amorphous phase by tie molecules and chain entanglements. As outlined in [73], the surface energy depends on the number of effective tie molecules and it can determine the crack-craze transition.

Separation between adjacent lamellae has been considered as the dominant molecular mechanism in SCG and ESC of polyethylene. In [75], the same mechanism has been identified in the fatigue of polyethylene. Several studies [76–79], discussed that the tie molecules are primary factor influencing creep and ESC rates. Also, the larger number of tie molecules and the higher the entanglement density, lead to the greater resistance to the failure [80–82]. However, researchers in [83,84], documented that crack growth is governed by the rate of disentanglement, and it is inversely proportional to the number of tie molecules.

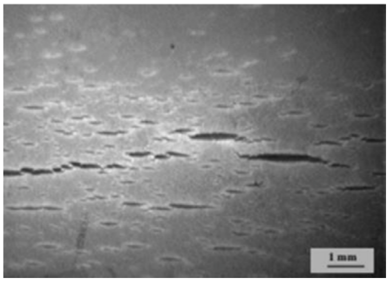

Fig. 7. The brittle failure of PE pipes; stage II (left) [74], and stage III (right) [91].

Brittle failure at the macroscopic level is related to the crack growth. The failure is associated to the craze resulted from voids, defects, and cracks created by fibrils fracture inside the craze [85–87]. As explained in [88], the breaking of chains has a minor effect on the process of the fibrils breakdown. The visual inspection can be used to categorize type of failure. The brittle failure in PE pipes at stage II and stage III are shown in Fig. 7. Generally, brittle failure and ductile failure can occur at the same time, however, the final failure depends on the specific circumstances, such as external load, oxygen, temperature, surrounding medium, microstructure, and defects. For instance, in [89], scratched PE pipes under pressure showed the brittle failure instead of ductile failure. In detail, a series of burst pressure tests for undamaged and variable notch depth PE pipes was carried out to determine the stages of pipes failure for maintenance purposes. In this context, the obtained burst pressures was taken into account as the residual burst pressures to modify stress controlled unified theory. Based on the obtained damage curves, the different stages of damage was specified. In another research works by Pinter et al. [90], the brittle fracture was observed in a pre-cracked PE specimen. The brittle fracture was characterized by smooth fracture surfaces after crack initiation.

The most frequent mode of failure for PE pipes is brittle fracture, which refers to the process of crack initiation at low stresses [92]. The lifetime before the brittle failure is often quite lengthy at low applied stresses. In [93], it has been discussed that at stress half of the yield stress, the brittle to ductile fracture transition occurred with SCG. In general, the most accurate and popular method for identifying whether a failure is ductile, brittle, or transitional is founded on the stress versus time-to-failure curves.

The effects of loadings and environment on the failure of PE pipe must be considered once pipes have been buried in soil. The literature review shows that study of the PE pipe failure behavior in the pipe-soil system is still a complex problem. We found that previous studies focused on three aspects of buried PE pipes: (i) stress and strength of PE pipes under mechanical overloads [94], (ii) the SCG [95], and (iii) the long-term behavior [96]. However, a few researchers investigated the combined loads, such as bending load and pressure combination [97]. An extant study [98], deals with hardening stiffness test to predict environmental stress cracking resistance (ESCR). The enhanced test eliminates the disadvantages of the subjective notching procedure and provides a more consistent and reliable ESCR picture. Considering the results, interlamellar entanglement is the primary factor controlling the SCG in PE. In a recent study by Qin et al. [99], ESCR of PE pipe was studied by exposure of pipe to various temperatures and hydrostatic pressures. Changes in the size of crystalline and amorphous, and variations in the phase composition, were also examined.

Based on the pipe diameter, the failure in pipes can be classified into longitudinal, circumferential or helicoidally failures [100]. A circumferential failure happens in small diameter pipeline where bending forces are predominant. In large diameter pipes, in contrast to bending stresses, hoop stresses are more significant, and longitudinal failure occurs.

As compact tension (CT) specimens have been extensively used in the area of fracture mechanics, the CT specimens of PE pipes were tested under constant tension in a manner similar to that used for testing metals in order to determine rule of the crack length a with time t. Lang et al. [101] conducted a series of creep crack growth experiments and determined the crack length as a function of loading time. In addition, they compared limitations of the approaches and concluded that effects of material aging on the lifetime modeling must be carefully evaluated. In Fig. 8, test equipment and a typical crack growth over the time are depicted.

An extant study [102], investigated failure mechanisms and mechanical behavior of PE pipes. In detail, the study was perform to determine effects of soil and pipe size, fault dislocation, and gas pressure on the mechanical behavior of PE pipe. The results indicated that the mechanical behavior of PE pipe is less affected by inner pressure, but it has a less resistance to PE pipe deformation. Hence, the proper inner pressure might be able to prevent some degree of PE pipe deformation in the fault area. Moreover, it has been determined that PE pipes with a larger standard dimension ratio (SDR) of a fitting and a smaller diameter are more likely to fail in the fault area.

By investigation on the literature, it is found that not only experimental tests, but also different numerical methods have been used to study failure of PE pipes. For example, in [103] a numerical study was carried out to investigate the damage of the PE pipes due to SCG. To this aim, LEFM was utilized to study stress distribution near the crack tip. Comparison of numerical results and creep crack growth tests confirmed that numerical method is an effective tool for lifespan estimation of PE pipes under various loading conditions. As LEFM was initially developed for metals, two key conditions must be satisfied in application of LEFM for polymeric materials [104]. Firstly, the specimen's overall loading condition falls within the range of linear viscoelasticity, and secondly, there is just a small area where plastic deformations can develop near the crack tip. Luo et al. [105], employed FEM to simulate PE pipe

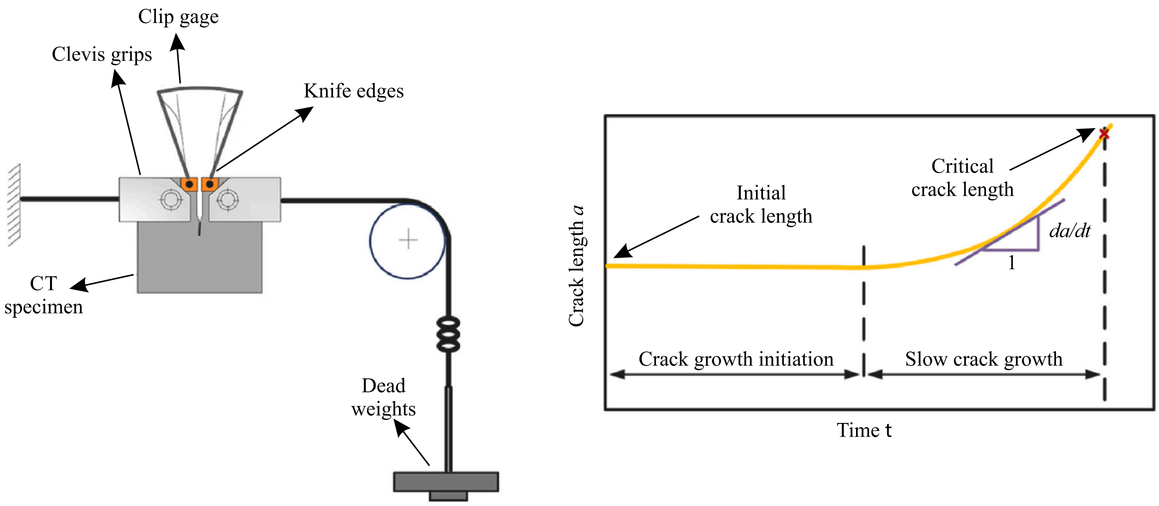

Fig. 8. Testing equipment for CT test (left) and changing the crack length with loading time (right) [101].

strength failure due to the foundation settlement. In this regard, the researchers used the hyperbolic model proposed by Suleiman and Coree [106]. It should be noted that the foundation settlement induced by natural disasters or non-standard excavation of large buildings cause leakage, pipe deflection or burst. According to the results of FEM in [105], it is concluded that the settlement displacement increases as the length of transition section increases, therefore, under the same settlement displacement, longer transition sections in PE pipes would increase safety. In [107], nonlinear FEM was utilized to investigate the behavior of pipelines buried in rainy forest regions. In this respect, the pipe element type was used to model the pipe and the ground is simulated with continuous solid elements. The specific weight of the layer was used to include the ground's drainage conditions. The results showed that the critical values are located in the wrinkle section, while the stress values are important and they approach the yield material stress. Later, behavior of PE under highly triaxial stress states was investigated by experiments and numerical study [108]. In detail, a hyperelastic-viscoplastic material model was used. An extant study [109], described numerical simulation of ductile fracture in PE pipes. To this aim, experimental results were used and the constitutive equation without the consideration of damage was established. The results confirmed that the FEM can successfully mimic the fracture and failure of PE pipes.

Later, in [110] extended FEM (XFEM) was used to investigate the fracture behavior of pre-cracked PE pipe. The pre-cracked pipe-soil model is illustrated in Fig. 9. Authors considered initial crack sizes and internal pressure as key parameters and determined effects of these parameters on ultimate bearing capacity. The results showed that the stress–strain relationship in the PE pipes involved two stages: (i) elastic stage and (ii) failure stage. It was also observed that the crack always grows at the thickness of the pipe prior to propagation along the pipe's circumference. At the same time, in [111], a 3D FEM model was established to study the mechanical behavior of buried scratched PE pipe under land subsidence. In this context, different parameters such as operating pressure, land subsidence displacement, soil gravity, and defect geometry were investigated to determine the effect of each parameter on the mechanical stress field. Considering the results, the effects of soil gravity can be disregarded, because of little influence on the von Mises stress of PE pipeline. Moreover, simulation findings indicated that scratch generates stress concentration in the pipe that risk of pipeline failure when internal pressure and external forces are combined (see Fig. 9).

In a recent study [112], a 3D numerical model was developed on LS-DYNA software to investigate damage of buried pipes under surface blast loads. A criterion considering deflection-to-span ratio damage was utilized. Based on the distance from the explosive and explosive charge, simulation results for various damage levels were obtained.

Over time, an extensive attempts have been devoted to develop constitutive models for study of viscoelastic and viscoplastic properties of PE material [113–115]. Literature survey indicates that there are different issues which must be taken into account in numerical simulation of PE pipes. For example, since the size of element has effect on the simulation results [116], the size of element cannot be chosen arbitrarily. In FE simulation of PE pipes, some assumptions such as defining an appropriate contact property between soil and pipe are necessary. Moreover, compared with the pipe diameter, the size of soil in the model should be large enough to simulate infinite soil. It is worth noting that, adequate test data must be provided to calibrate the parameters and improve numerical models.

4.2. Lifetime prediction in PE pipes

Since PE pipes have been utilized for transporting water and gas and play a crucial role in lifeline engineering, the lifetime prediction of these pipes has become a critical task. Consequently, different methods and techniques have been developed to investigate and predict lifetime of PE pipes. Considering previous research works, we have divided lifetime of PE pipes into (i) mechanical lifetime, and (ii) chemical lifetime. In this section, we review prediction methods in the above-mentioned lifetime categories.

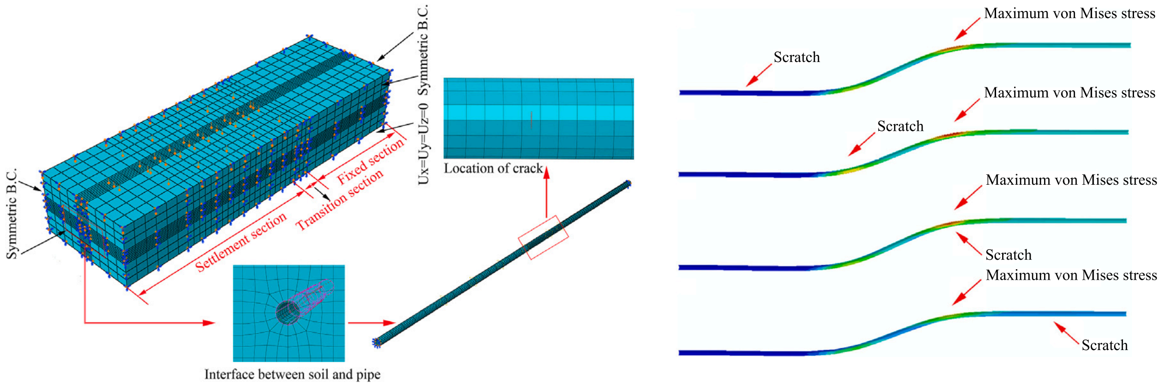

Fig. 9. A model for pre-cracked pipe-soil (left) [110], and Distribution of von Mises stress in buried PE pipe with a scratch at various locations (right) [111].

– Prediction methods to estimate mechanical lifetime

The most popular technique for assessing long-term performance and predicting lifespan is developed based on the hydrostatic experiment on the pipes [117]. As discussed in [118,119], profound knowledge and understanding SCG of PE pipes are crucial for determining their lifetime and level of safety. In this context, LEFM technique has been used to estimate the crack propagation lifespan of PE pipes, but the resistance against crack growth is nature of material. Three major tests for prediction of the lifetime of PE pipes are: (i) hydrostatic test, (ii) SCG test, and (iii) cycle load test.

In hydrostatic experiment, the standard extrapolation approach is used to estimate the long-term lifespan of PE pipes at standard temperature [120]. In ISO 9080, the lifetime of PE pipes at the real environment can be extrapolated by a few equations considering the stress, temperature, and time to failure. The core of this technique is rate process method (RPM) and the Arrhenius equation serves as its foundation:

$$K = A\ exp\left(-\frac{E}{RT}\right) \tag{1}$$

where K indicates reaction rate, and T denotes the absolute temperature K. In addition, E indicates apparent activation energy, while A and R are the frequency factor and gas constant, respectively. The failure time (t) and temperature (T) have the following relationship:

$$\log(t) = A + \frac{B}{T} \tag{2}$$

The following equation demonstrates a linear relationship between failure time and the stress (σ) on the log–log axis.

$$\log(t) = A + B\log\sigma \tag{3}$$

Combining Eqs. (2) and (3) gives an RPM model. ASTM D2837 and ISO 9080 use a three-parameter model and a four-parameter model, respectively.

$$\text{Three-parameter: } \log(t) = A + \frac{B}{T} + \frac{C\log\sigma}{T} \tag{4}$$

$$\text{Four-parameter: } \log(t) = A + \frac{B}{T} + C\log\sigma + \frac{D\log\sigma}{T} \tag{5}$$

where A, B, C, and D are constants. Also, t denotes the failure time. σ and T are stress and absolute temperature, respectively. According to ISO 9080, various samples' failure times are different when subjected to the same temperature and stress. In [121], a combined experimental and analytical framework is developed to accelerate lifetime estimation for PE pipes. Currently, PE pipes must have a 50-year minimum design lifetime. The permitted range of rated pressure affected by the pipe thickness, diameter, and safety factor and it is determined using the hydrostatic design basis and the minimum needed strength.

There exists a considerable body of literature on application of LEFM in SCG in polymeric materials. However, it should be considered that LEFM is valid when the plastic deformation is restricted exclusively to the leading edge of the crack. Therefore, the stress field near to crack tip can be characterized employing LEFM. Based on LEFM approach, the applied stress intensity factor (K_I) determines the crack growth rate under static loads, in accordance with the following Paris-Erdogan equation [47]:

$$\frac{da}{dt} = A\left(K_I\right)^3 \tag{6}$$

$$K_I = \sigma.\sqrt{a}.Y \tag{7}$$

where A and m are constants and depend on the material and testing variables (e.g., temperature and environment). In addition, Y is the shape factor, a and σ are the crack length and applied stress, respectively.

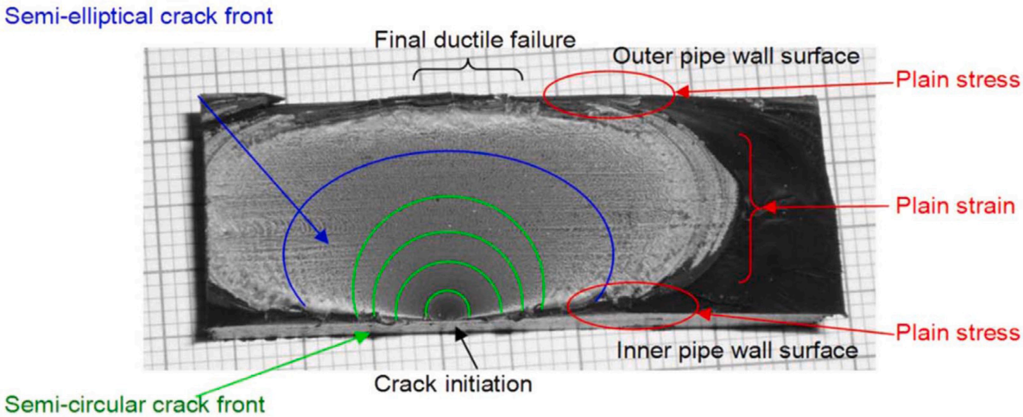

Fig. 10. The fracture surface of the PE pipe after internal pressure experiment [133].

An prediction of the remaining lifetime under a particular set of circumstances can be made by understanding the SCG behavior. A modified Paris-Erdogan equation and the stress intensity factor can be used to estimate lifetime, which is based on the LEFM [122]. In this context, a set of parameters must be used. Particularly, internal pressure, material parameters, and the initial crack size are the most important. Moreover, in [123] it has been discussed that the influence of residual stress is important parameter as well. Lifetime prediction based on the fracture mechanics is feasible by using material constants of creep crack growth and Paris law. In a study [124], fracture tests have been conducted at different testing speeds and temperatures. The behavior of crack propagation was described over several decades of time-scale based on a time–temperature superposition approach. The developed analytical model was used and the lifetime of pressurized pipe was predicted.

In PE pipes containing cracks or defects, the total failure time would be sum of the time for crack initiation and the time for SCG. It should be noted that the crack growth is relatively slow, and when an initial crack reaches to the critical crack size, failure occurs. Although LEFM technique has been used for prediction of PE pipe lifetime in previous research works [125–128], experimental practices are required to prove correlation between the actual lifespan of the pipe and the failure time estimated by LEFM.

In cyclic loading test, two group of specimens (i) cracked round bar, and (ii) dumbbell-shaped specimens have been utilized to determine lifetime of PE pipes, but the first group of mentioned specimens is more widely utilized and investigated [129]. In previous studies [130,131], it has been discussed that the findings from cyclic load tests and hydrostatic experiments are highly congruent for various grades of PE pipe materials.

In cyclic loading test, the frequency (f) has effect on the time of crack initiation and SCG. Hence, the change in crack length per cycle N is known as the crack growth rate, using following equation:

$$\frac{da}{dN} = A\left(K_I\right)^m \tag{8}$$

Any stress ratio (R) has no effect on the material characteristics A and m in the Paris-Erdogan formula. To obtain the crack growth rate per unit time, the fatigue crack growth rate is multiplied by the frequency:

$$\frac{da}{dt} = \frac{da}{dN} \cdot f \tag{9}$$

In [132], the PE pipe's fatigue creep curve is calculated using this extrapolation method at the application temperature. Frank et al. [133] combined cyclic cracked round bar experiment and LEFM and proposed a new method for lifetime prediction. In detail, extrapolation was utilized following the development of SCG curves at various loading ratios, to develop the SCG rates. Fig. 10 shows a fracture surface of a PE pipe after internal pressure test. The striations indicates the SCG propagation. Advantage of the proposed method was its capability in providing the load-depending lifetime information based on the SCG. The developed method was used for four different PE pipe grades and predicted their lifetimes.

In a study [134], a short time test technique was used to evaluate the SCG in different PE pipes. Researchers continued the attempts, and later in [135] the lifespan of PE pipes at operating conditions was predicted based on the fatigue lifetime prediction method. In detail, digital image technology was used to measure the crack length. In Fig. 11 extrapolation methodology and comparison of measured and predicted failure times are illustrated.

– Prediction methods to estimate chemical lifetime

During storage or usage, performance of polymers and things they produced would be eventually decreased due to the effects of the ambient conditions. Although several studies confirmed influence of sudden or dramatic seasonal changes on the failure of the metallic pipes [136–138], the ability of PE pipes to withstand thermal expansion proved that the temperature variation has a little effect on the failure of these pipes. The chemical lifespan of PE pipe is related to the free radicals. In fact, the chemical lifetime

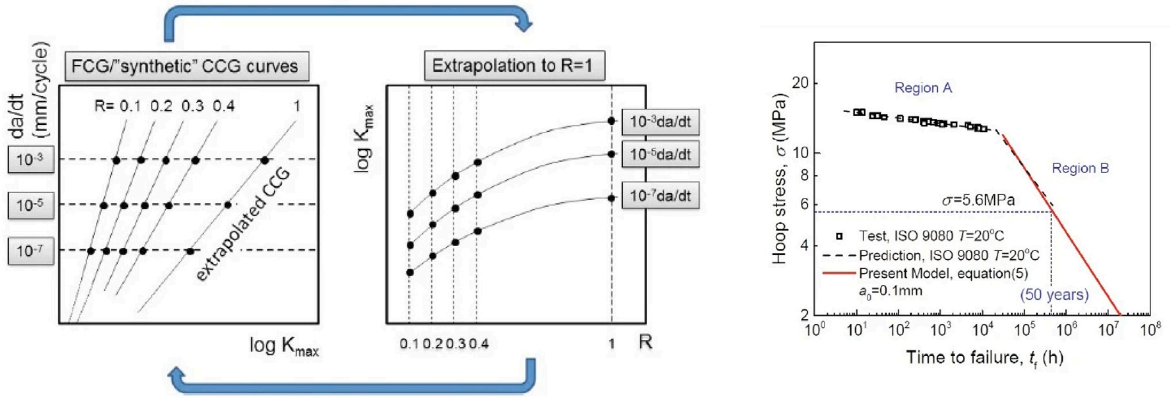

Fig. 11. A methodology for generating synthetic SCG curves (left) and comparison of failure times measured by internal pressure experiment (right) [135].

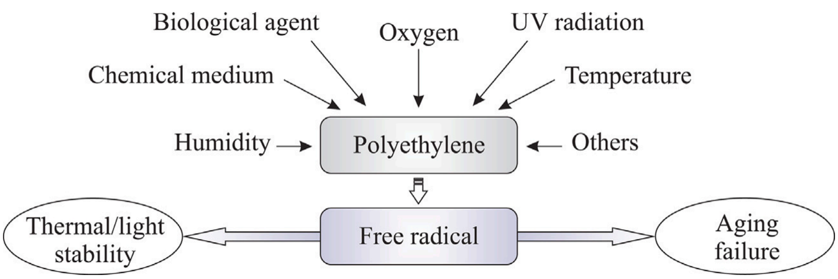

Fig. 12. The relationship between the environment and chemical lifetime of PE pipes.

is defined as the interval between the stability and aging failure of PE material, as shown in Fig. 12. Avoiding the formation and propagation of the free radicals can lead to ensuring performance and an increase in the lifetime.

Since lifetime of polymeric material is linked to the behavior of consumption and diffusion of antioxidants, different studies [139–141] have investigated efficiency of antioxidants or their mixtures. Moreover, efficacy in short-term usage at high temperatures or similar exposure conditions have been studied [142–144]. As discussed in [145,146], a critical concern is the diffusion and consumption of antioxidants in the pipe walls as a result of thermo-oxidative aging. Experimental tests presented in [146] showed a loss of more than 80% of the initial antioxidant content during the first 1000 h of pressure testing.

Influence of chlorinated species on the failure of PE pipe is another important domain in this field. Particularly, the early loss of antioxidant stability based on the chlorinated species makes thermo-oxidation possible [147]. The oxidation offset temperature (OOT) or oxidation induction time (OIT) are used to determine thermo-oxidative resistance of PE material [148]. Based on linear relationship of OIT and the concentration of phenolic antioxidant, it can be utilized to determine lifetime of PE pipes. As has been previously reported in the literature, lifetime prediction models can be developed based on Arrhenius equation for the PE pipes subjected to the hydrostatic test [149], and PE gas pipes subjected to thermo-oxidative aging [150]. In this context, the life prediction based on hydrostatic test is:

$$\ln(\mathrm{OIT}) = S_T \times t + \ln\left(\mathrm{OIT}_0\right) \tag{10}$$

$$\ln\left(S_T\right) = -\frac{E_a}{R} \times \frac{1}{T} + \ln C \tag{11}$$

where T denotes absolute temperature. Also, t and S_T indicate exposure time, and the rate of depletion of antioxidants, respectively. OIT_0 is initial OIT for unexposed PE pipe, and E_a denotes the activation energy of the reaction. In addition, R and C are the gas constant, and a constant independent of experiment temperature, respectively.

The following equations can be used for aging-based thermo-oxidative life prediction:

$$\ln(P) = -K \times t + \ln(B) \tag{12}$$

$$\ln(K) = \ln(A) - \frac{E}{R} \times \frac{1}{T} \tag{13}$$

where P indicates the ratio of properties before and after aging. Also, B and t denote initial value of property, and the exposure time, respectively. At room temperature, the results of the aforementioned techniques for lifespan prediction are more than fifty years.

After consumption of antioxidant, PE material degrades quickly. For lifetime prediction based on hydroperoxides, the following equation is proposed in [149]:

$$\ln(\mathrm{ROOH}) = S_T \times t + \ln(\mathrm{ROOH}_0) \tag{14}$$

$$\ln\left(S_T\right) = \frac{E_a}{R} \times \frac{1}{T} + \ln C \tag{15}$$

where for test temperature T and exposure duration t, the pipe's ROOH value represents the hydroperoxide oxidative products. S_T denotes the reaction rate, and ROOH_0 indicates initial ROOH value for the unexposed PE pipe.

The aim of accelerated aging of PE pipes indoors is accelerating the chemical process of degradation. As described in [151], the degradation of PE pipes is often identified by physical or chemical methods, such as molecular weight analysis, cross-linking behavior, and melting behavior. Since the mentioned techniques are not appropriate of evaluation of PE pipes in real application, it was essential to determine the link between the macroscopic physical properties and the microscopic mechanism of aging. At the micro scale, aging has been inspected by modulus analysis, tensile elongation rate, fracture test, and other mechanical experiments. For instance, the modulus of elasticity [152] and hydro-axial tension test [153] of PE pipe materials were used to identify how their characteristics degraded, and then merged them with the Arrhenius equation to estimate the lifespan. The prior research works investigated the aging rate of PE pipes affected by thermo-oxidation. For instance, it was investigated by glass transition temperature [154], local embrittlement [155], failure strain [156], and other properties [157].

Although both mechanical and chemical failure modes have been predicted by different methods, there are limitations and challenging issues in this domain. For example, two limitations in mechanical lifetime prediction are as follows: (i) an increasing in the stress, can shortened the long-term hydrostatic test, but it can lead to the ductile–brittle transition of PE pipes, and make a deviation from real failure. In addition, influence of defect and material aging on the durability of the PE pipes are not considered in hydrostatic test. Therefore, there is a significant deviation between the outcomes of hydrostatic test and the operating conditions. (ii) There is a lot of uncertainty in crack initiation and growth in PE pipes, since information on the dimensions, location, and configuration of the initial crack is lacking. For instance, the time of crack initiation depends on the geometry of the initial crack. Therefore, crack growth is different in the notches created by fatigue pre-crack or a razor blade. The current lifetime estimation techniques for the initial crack growth are based on Paris-Erdogan relationship between the stress intensity factor and the creep crack growth rate. Indeed, the transient effects (initial stage of crack growth) and creep crack growth are neglected. Since the crack initiation has a major contribution on the failure, it has a key role in prediction of lifespan of the PE pipes.

Similarly, there are limitations on prediction of the chemical lifetime. For instance, two complications and limitations in prediction of chemical lifetime are as follows: (i) correlation between the matrix aging and antioxidant depletion is a complicated issue. In [158], researchers indicated that there is no distinct time boundary between antioxidant depletion and material aging degradation, and these processes often occur at the same time. In fact, when hydroperoxide in PE pipes reaches a threshold level and the antioxidant is entirely consumed, the characteristics of PE pipes would be considerably diminished. But currently, PE pipe deterioration does not progress to the point where its qualities are noticeably diminished. Therefore, further research works are required. (ii) Thermal degradation process of PE pipes is affected by diffusion-limited oxidation (DLO) which demonstrates the relative connection between the supply and consumption of oxygen. As described in [159], DLO is a crucial element in the distinction between actual aging behavior under service conditions and accelerated thermo-oxidative aging. Several parameters such as the rate of oxygen depletion and geometry of the material have effects on the DLO. The available lifetime prediction techniques use Arrhenius extrapolation to estimate lifespan using limited temperature and number of data points. In this regard, inhomogeneous degradation process of the material is disregarded, and non-linear temperature change and mechanical changes are not accommodated. Since there is a lack of experimental research works on the multiple cracks initiation of PE pipes under thermo-oxidation aging, further investigation is required in this field.

5. Challenges and future prospects

The quality and lifetime of PE pipes depend on several parameters. Although there is a rapid development in fabrication and applications of PE pipes, there are different challenging issues which some of them are listed as follows:

- Although the manufacturers of PE pipes and fittings have made significant efforts to ensure compatibility of joint systems and piping materials, a lot of failures in joint systems are observed. Therefore, it seems necessary to consider this type of failure in prediction approaches.

- Literature investigation confirmed that LEFM concepts have been used to study crack growth in PE pipes, but there are some limitations which need further investigations. For instance, the LEFM technique would either be invalid or significant adjustments are required, if extensive aging of a pipe material occurs under real-world service conditions.

- The majority of the material typically experiences stresses and strains in the linear-viscoelastic range (less than 2 MPa) when it is present in the unbroken ligament of a fracture mechanics sample, but PE pipes under internal pressure generally are exposed to stress levels in the nonlinear-viscoelastic range (more than 4 MPa). Effects related to the nonlinearity might be large or insignificant, depending on its level. Therefore, further examination is required to determine under which circumstances the elastic-viscoelastic correspondence principle, is violated and LEFM approach cannot be used for real pipe loading situations.

- The hydrostatic tests have been performed on different PE materials, but the demands of rapidly expanding material qualities have made the present hydrostatic tests increasingly insufficient. In general, one year of test time is required for the lifetime prediction based on hydrostatic test. This time would be longer while PE material is improved. Hence, it is necessary to identify new alternatives or enhanced test methods, considering an acceptable agreement between experimental findings and long-term operational results in ambient environments.

- Although PE pipes made from recycled resins have a number of benefits and they can help to solve problem plastic pollution, an extensive research is required to study structural performance of PE pipes made with post-consumer recycled materials. Indeed, the presence of contaminants has effect on the long-term performance of pipe and this issue needs to be addressed. In this context, it is essential to develop creative recycling techniques for high quality recycled PE pipes.

- In the current acceleration techniques, the pipe's micro-mechanics and the interaction between material aging and stress cracking are not considered. Moreover, in hydrostatic experiment, the material is influenced by temperature, stress, and thermooxidative aging, but the influence of aging on the pipe failure is ignored, compared to the influence of stress. For solving these issues, a model considering chemomechanically coupled theory might be effective to investigate coupled effect of the material aging and crack growth on the PE pipes.

Different parameters such as the mechanical state, application conditions, and the environment have crucial effect on the life of PE pipes. Only when all effects of these parameters are known, determining the lifetime can be justified. Indeed, different parameters of the external environment must be considered, to obtain a more accurate and reliable lifespan prediction.

6. Conclusion

Applications of PE pipes in water and gas industries have been significantly increased. Consequently, PE pipes have become part of our life and our industries which need further investigations. The current study, present a review on the failure of PE pipes. To this aim, all failure modes of PE pipes have been described and findings of previous research works have been discussed. In order to develop a lifetime prediction model, it is necessary to understand the common mechanisms of pipe failure. We have reviewed different approaches which have been used to predict mechanical and chemical lifetime of PE pipes. Review and analysis of proposed approaches confirmed that how these techniques can save the time and cost. Although lifetime of the new pipes and the pipes which are subjected to accelerated aging can be predicted by current lifetime prediction techniques, prediction for in-service pipes is still lacking. Our discussion in this paper shows the advantages and limitations of the lifetime prediction methods. Considering current review, we have concluded several challenges in this field which are briefly described. Based on the material developments, successful applications of PE pipes, and different lifetime prediction approaches, further development and research are expected.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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