# State-of-the-Art Overview of Plastic Pipe Deterioration Mechanisms

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## ABSTRACT

Plastic pipe material is increasingly used for several applications including water, sewer, and gas applications. Plastic pipelines currently in service are generally not as old as the metallic pipelines, but there have been many seemingly premature failures warranting a comprehensive understanding of their failure mechanisms and how to keep track of them for appropriate intervention. This study provides a comprehensive review of the deterioration mechanisms for plastic pipelines informed by the state-of-the-art literature. There have been numerous papers published on various aspects of plastic pipe degradation in multiple utility sectors, and this proposed paper synthesizes the most crucial knowledge out there into a single paper for practical reference. Various material, design, installation, operational, and maintenance-related factors could affect premature failure of plastic pipelines. All such factors are highlighted in this paper. This paper is useful for utility owners and consultants dealing with any kind of plastic pipelines.

## INTRODUCTION

Technological innovations during the past decades made plastic pipes such as polyvinyl chloride pipes (PVC) and polyethylene pipes (PE) some of the most popular materials of choice in piping systems for different services such as water, gas, sewer, and wastewater (Barker et al., 1983). In the 1980s, PVC pipes were considered the first material of choice for low-pressure pipes. During the post-2000s, PE also gained wide acceptability for urban water distribution systems (Tsakiris & Tsakiris, 2012). According to the global piping market, in 2002, PVC and PE accounted for 39% and 20% of the pipe raw material market, respectively (Saad et al., 2012). In 2018, PVC and PE resins accounted for about 40% of plastic demands distribution in Europe, making these types of plastic pipes the most common material of choice for piping systems in Europe (Beuken et al., 2012; Geudens & Kramer, 2022; PlasticsEurope, 2019).

The current perception regarding plastic assumes about a 50-year lifetime for different services (Lee et al., 2016). The common misconception in plastic pipes in service is that failure will occur only if the critical value of the plastic strain is surpassed (Hermkens et al., 2008). A combination of factors could result in a premature failure in plastic pipes much sooner than the expected lifetime, just as it could happen with other pipe materials. There are many incidents where premature failure in a plastic pipe hindered the service and required immediate maintenance. Incidents such as four failures in PVC water supply after 11 years of service, fracture in a PVC pipe wall only after 16 years of service, and leakage of HDPE pipes after 6 years of service are among many premature failure incidents of plastic pipes in service (Farshad, 2011). Also, other failures such as crack initiation in the pipe's elbow (Gagné & Banuta, 2020), premature joint failure in a contaminated joint (Tayefi et al., 2015), contamination of water by thermal degradation of plastic pipe (Isaacson et al., 2021), and over-belling defects during installation (AWWA, 2022) are among common premature failure incidents in plastic pipes.

This paper describes different deterioration and damage mechanisms of plastic pipes through a review of the state-of-the-art literature. The most common causes of premature failure during manufacturing and installation, and important environmental factors stimulating failure in plastic pipes are discussed.

## MAJOR FAILURE MODES IN BURIED PLASTIC PIPES

The most common failure mechanisms in plastic pipes in different conditions are discussed in this section. These failure modes either directly or indirectly drive the pipe to leakage and other issues resulting in eventual service failure.

**Fracture and Cracking.** Plastic pipes may experience fracture and cracking due to factors such as externally applied load, chemical agents, thermal gradients, production errors, etc. Cracking in pipes can be categorized based on their behavior into two different features, ductile and brittle. Ductile rupture occurs when the internal pressure exceeds the pipe's strength capacity. During this failure mode, plastic pipe is capable of showing its full-strength capacity with a noticeable plastic deformation (Maupin & Mamoun, 2009). Generally, at room temperature and low loading speed, plastic pipes tend to show ductile behavior during service; however, a high-stress point originating from any inclusion, defects, contamination, etc., in a low temperature service condition and high loading speed may initiate a brittle failure (Farshad, 2011). The brittle fracture at low stresses below the yielding point is the most common failure mode for plastic pipes (Krishnaswamy, 2005).

Long exposure of plastic pipes to circumferential stresses below the yield point can result in slow crack growth (SCG) (Maupin & Mamoun, 2009). This failure is categorized as brittle failure exhibiting little plastic deformation. For SCG to occur, an initial point as a high-stress point is needed which is caused by inclusions, contaminations, scratches, defects, etc. from different phases in the plastic pipe's lifetime. When load and pressure are applied on this point, a brittle crack may initiate and grow along pipe's length at a very slow speed (Poduška et al., 2019). Resistance to SCG can be improved by increasing molecular weight and decreasing crystallinity. Therefore, any condition that contributes to decreased molecular weight or increased crystallinity of plastic pipes enable brittle behavior and potential onset of SCG failure mode (Krishnaswamy, 2005).

In SCG failure mode, the crack growth rate is low; however, in some plastic pipes, sudden longitudinal brittle fractures with a length up to several meters have occurred. This is known as rapid crack propagation (RCP) (Scholten et al., 2014), a long fast-moving brittle crack with longitudinal direction. Certain conditions and variables, such as temperature, pipe dimensions, material properties, residual stress, processing, service conditions, and internal pressure, are required for RCP to occur (Farshad, 2011; Scholten et al., 2014). RCP does not stop till it reaches a mechanical joint (Venizelos et al., 1997). Sometimes, in the cases of butt-fused joints, RCP may run through pipe's joint (Palermo, 2012; Ruchti, 2017).

Crazing, as a precursor to cracking, is another failure mechanism that can significantly contribute to plastic pipe degradation. Inclusions, local stress concentration region, material defects, and residual stress produce stresses resulting in yield zones which will lead to a craze (Farshad, 2011). Craze is not a major failure mode by itself in plastic pipes, but it can result in cracks throughout the pipe (Wolters, 1998).

**Deflection and Buckling.** Insufficient stiffness and flexibility of plastic pipes, compared to other rigid pipe materials, makes them more vulnerable to buckling (Moser & Folkman, 2008;

Suleiman, 2002). When a pipeline or a section of the pipe is subjected to compressive loads and bending moments, compressive stresses and strains are applied to the pipe structure. While withstanding lateral loads and internal pressure, plastic pipes may lose their stability and buckle locally or show a significant deformation if the loads reach a critical value (Motavalli et al., 1993; Xie et al., 2020).

Factors affecting the buckling behavior of buried pipelines are burial depth and pipe diameter-to-thickness ratio (Liu et al., 2017). Local shell mode is the dominant buckling mode for a buried plastic pipe with a large diameter-to-thickness ratio or deep burial depth (Yun & Kyriakides, 1990). Snap-through, a type of local buckling in buried pipes, occurs when the surrounding environment is stiff. In the case of pipes with stiffness larger than the soil, ovalization is the dominant deflection mode (Farshad, 2011). In elevation variation or inter-trench pipe connections, if the bent radius is not large enough, local buckling in the bending section of the pipe may occur (Shima et al., 2014; Zhang et al., 2022).

A pipe with a small diameter-to-thickness ratio and shallow burial depth tends to buckle in the beam mode, also known as the upheaval buckling mode. When the pipe's temperature and pressure increase due to operational conditions, the pipe tends to expand and buckle in an upward direction because it is constrained. Upheaval buckling can also result in local shell buckling in more severe cases. Recovering the pipe after this failure is expensive and time-consuming; therefore, in cases of damaged pipes, the whole section must be replaced (Ommundsen, 2009; Yun & Kyriakides, 1990).

## FACTORS AFFECTING PLASTIC PIPE DETERIORATION

Different phases during the pipe's lifetime have an impact on its performance. These phases include manufacturing, storage, installation, and service. Influential factors can be different depending on the phase.

**Manufacturing.** During the manufacturing of plastic pipes, the boundaries of the polymer primary particles should convert into a homogenous product. This process is known as gelation, and the ductility of plastic pipe is shown to be mainly dependent on the degree of gelation (Hermkens et al., 2008; Visser, 2010). A lower level of gelation causes the plastic pipe not to maintain its crack resistance during aging. A 60-85% gelation level will result in optimum fracture toughness, strength, crack resistance, and impact strength (Breen, 2006).

Krishnaswamy (2005) concluded that the primary material properties contributing to the ductile behavior of plastic pipes are density or crystallinity. The degree of crystallinity also depends on the cooling rate of the polymer melt during extrusion: the slower rate of cooling, the higher degree of crystallinity (Davis et al., 2007), and the lower resistance to SCG. Another critical factor in the manufacturing process is the temperature. Plastic pipes can develop brittle performance in a low manufacturing temperature (Awaja et al., 2016; Barton et al., 2019).

Manufacturing defects such as porosity and inclusions may occur during pipe production. Porosity is caused by air trapped in the mold, and inclusions are caused by unintentional material entrance during production. All these defects break continuity in the pipe and develop high stress points (Barton et al., 2019).

**Storage and Installation.** During the installation process, plastic pipe segments can be damaged in different ways: being struck by installation tools, rough handling of pipes by workers, fracturing the pipe by gouging, joining errors, and bad storage conditions are among the common reasons for damaging pipes in the field. Dragging the pipe across the field can abrade the pipe surface. Any impact to the pipe by tools or equipment also can damage the surface depending on the magnitude of the impact (Lee et al., 2016; Mock Carroll, 1985). Improper bedding conditions, such as a faulty backfill with coarse soil, can cause point loads to the surface (Kirby, 1981). In improper storage, by exposing the pipe to the sun, ultraviolet (UV) components can promote and accelerate oxidation in pipe surface. This is known as photo-oxidation.

Regarding the installation of fittings, the pipe surface must be cleaned before joining; otherwise, an improperly cleaned pipe surface can result in surface contamination and early failure (Davis et al., 2007; Mock Carroll, 1985). Defects or failure in heat fusion welded joints in PVC or PE pipes as a result of high pressure during pipe joining (Rahman & Watkins, 2005), or over-insertion in gasket joints are among the prevalent defects in plastic pipe joints (Rahman & Watkins, 2005; Youssef et al., 2008).

**Environmental Factors.** During craze formation, some local yielding may occur due to high-stress points and result in void formation. In the presence of an aggressive medium, these voids will absorb more aggressive fluid, which reduces the yield strength of the material and may eventually lead the pipe into cracking (Farshad, 2011)

Aggressive agents can chemically affect plastic pipe material properties and structure in different environments. Craze initiation is accelerated at high chemical concentrations. Aggressive agents are prevalent in different mediums. Natural gas contains higher hydrocarbons, such as aliphatics (Wolters, 1998). Odorants, such as mercaptans, are also added to the gas for odorizing to enable the public to detect line leaks. Water disinfectants are added to the water for the elimination of microorganisms and water contaminations in municipal water supply systems (Khan et al., 2020; Yu et al., 2011). Common techniques for disinfection of water pipeline systems include chlorination by hypochlorite (HOCl), Chlorine dioxide ($CLO_2$), Chlorinated water ($Cl_2$), ozonation, etc. (Bredács et al., 2018b; Symons, 1977; Yu et al., 2011, 2015). The reactivity of HOCl and $ClO_2$ with polymetric materials results in accelerated antioxidant consumption and material embrittlement, which can lead to the early degradation and premature failure of plastic pipes (Colin et al., 2009; Van Der Stok et al., 2018).

Additives such as phosphites, hindered phenol antioxidants, and stabilizers are added during the manufacturing process of plastic pipes to prevent chemical degradation in service. These additives inhibit oxidation caused by exposure to chlorinated water and prevent brittle cracking. This protective feature of plastic pipes is beneficial until antioxidant depletion happens in cases of extreme exposure to chlorine (Ghabeche et al., 2015; Mitroka et al., 2013). There is not a specific concentration above which plastic pipe loses its antioxidative capability. Exposure to aggressive agents present in pipeline systems exposes the plastic pipes to a more brittle behavior, by which pipes will be susceptible to brittle cracking failure mode. For municipal water distribution services, it is recommended to use sodium hypochlorite (NaOCl), and hypochlorous acid (HOCl) rather than chlorine dioxide ($ClO_2$), and chlorine ($Cl_2$) for disinfection purposes. These additives have a lower degree of aggressiveness for plastic pipes in the long run (Bredács et al., 2018a, 2018b; Chung et al., 2007; Nguyen et al., 2021). In addition, a higher molecular weight of HDPE compared to PVC and MDPE makes them a better choice for aggressive environments (Hayes et al., 2011; Wu et al., 2013; Zhu & Hamielec, 2012).

## DISCUSSION

In previous sections, different damage mechanisms of plastic pipes and different factors contributing to pipe's failure are discussed. It is important to distinguish between the key factors that initiate the failure mechanism and the ones deteriorating it. In the following, based on the review of the deterioration factors for plastic pipelines informed by the state-of-the-art literature and the authors' interpretation, the step-by-step process of a premature failure in a plastic pipe is explained and illustrated.

**Cracking Failure in Plastic Pipes.** Despite being resistant to operational pressure and environmental loads, plastic pipes may experience premature failure in the middle of operation. A premature failure of plastic pipes does not always result in a complete collapse, but a small failure in the pipe wall can lead to leakage and eventually, service failure. This step-by-step process is influenced by different phases during the plastic pipe's lifetime.

After the formation of a high-stress point, these concentrated local stress regions result in craze formation, which is the initial condition for crack formation in pipe walls. Before discussing the crack growth phase, it is imperative to discuss chemical degradation in plastic pipes.

Plastic pipes are designed to withstand chemical deterioration based on their material properties, stabilizers, and antioxidants added during manufacturing. They can resist chemical deterioration resulting in SCG on pipe's wall. Some special conditions need to happen for a pipe to deteriorate chemically during its service. Plastic pipes' extreme exposure to acidic environments depletes the plastic's antioxidant particles. These chemical agents are capable of:

- accelerating the craze initiation at lower stress and weakening of craze fibrils (Breen & van Dijk, 1991; Wolters, 1998)
- loss of ductility by an increase in crystallinity (Khan et al., 2022; Vertova et al., 2019)
- crack propagation by stabilizer and antioxidant depletion into the pipe wall (Yu et al., 2011)

Crack propagation due to extreme exposure to an aggressive environment is known as environmental stress cracking (ESC). Here, a crack initiates through the oxidated section of the pipe. After a while, acidic agents can penetrate through the crack into the pipe wall and cause the crack to grow more into the wall (Yu et al., 2011). Long exposure time is required for ESC formation in plastic pipes because antioxidant depletion is not a fast phenomenon, but some conditions can accelerate it. During its service, if the plastic pipe is exposed to high temperatures and high humidity, the rate of antioxidant depletion is higher (Merah, 2007).

An interesting point about the relationship between craze and chemical agents is that they both influence each other. Void formation because of crazing allows more aggressive fluid to be absorbed. In addition, a higher absorption of aggressive agents reduces the yield strength of the material and accelerates craze formation by weakening its fibrils. In other words, acidic agents accelerate crazing and craze formation, letting the chemical agents penetrate the pipe wall.

Cracks, as a product of crazing, are the next phase of the damage mechanism in plastic pipes. A crack can be ductile or brittle, depending on environmental factors. A ductile rupture occurs when internal pressure during service exceeds the plastic pipe's strength. This type of cracking shows a noticeable plastic deformation before rupture. In ductile rupture, the crack growth rate is limited; therefore, it does not occur abruptly, which is preferable for utility companies to inspect and fix.

The ductile behavior of cracks is not always the case, and many factors cause the cracks to become more brittle. In fact, most of the premature failure incidents of plastic pipes are brittle cracks. If a high-stress point in the pipe is exposed to relatively low loads below the material's yield point over a long period of time, SCG, a crack with brittle behavior, occurs. The plastic pipe itself has an SCG resistance feature but factors such as high crystallinity and chemical deterioration weaken the SCG resistance of plastic pipes. SCG does not show a noticeable plastic deformation before rupture and occurs abruptly as premature damage. In rare cases, the RCP damage mechanism occurs when internal pressure beyond critical pressure is combined with a sudden pressure surge in certain thermal conditions. This damage mode has a rapid crack growth rate and may propagate up through pipes' joint.

All these cracking modes result in service failure at the pipe; however, the brittle cracks are more catastrophic. SCG occurs under pressure lower than the yielding point of material and grows without showing any plastic deformation; as a result, the length of SCG is higher than ductile rupture, and the leakage is more severe. In RCP failure mode, the crack length is much longer, and in the cases of butt-fused joint pipes, cracks can propagate through pipes' joint. Despite being a rare case, leakage in RCP can only be dealt with by replacing the pipe.

**Buckling and Deformation Failures in Plastic Pipes.** Buckling and deformation are other important failure mechanisms that compromise the pipeline's serviceability. Pipes under certain compressive loads and bending moments show local deformation resulting in a reduction of load-bearing capacity. The buckling phenomenon may not result in leakage directly, but it contributes to other failure mechanisms causing leakage. A decrease in the pipe's load-bearing capacity, especially where the compressive stress/strain reaches its peak, accelerates premature rupture in the pipe's wall. An important point regarding plastic pipes is their lower stiffness compared to other rigid pipe materials. More flexibility of plastic pipes makes them more vulnerable to buckling and deformation. Within the most common types of plastic pipes in different services, PE is more flexible than PVC and shows more deformation under a certain external load. In addition to stiffness, other factors such as burial depth, wall thickness, diameter-to-thickness ratio, and operation pressure affect plastic pipe deformation.

The upheaval mode tends to occur for a pipe with a small diameter-to-thickness ratio and shallow burial depth. Depending on the severity of upheaval and bending radios of the pipe, bulge and local buckling at the peak of the pipe may occur. The critical strain is higher in the case of pipes with thicker walls. For pipe operation pressure, an increase in the pipe's design pressure generally results in a lower critical axial strain which results in local buckling. Also, the initial circumferential stress in pressurized pipes makes them more resistant to buckling (Liu et al., 2017; Ommundsen, 2009; Yun & Kyriakides, 1990).

Based on the most common failure modes and influential factors, some recommendations can increase the reliability of buried plastic pipeline systems. Preventing high-stress points from emerging in plastic pipes is a major step to prevent brittle cracking. Major sources of high-stress points are in manufacturing and installation. It is important to have a detailed inspection of the backfill and prevent coarse soil during installation. It is also recommended to use NaOCl and HOCl for water disinfection instead of $ClO_2$ and $Cl_2$.

## CONCLUSION

Multiple conditions during a plastic pipe's lifetime can result in premature failure which designers and utility companies do not expect. In the manufacturing, storage and installation phases, high-stress points as a local stress concentration region are formed. These points are mostly results in craze initiation, and because of that, cause crack failures in pipe walls. Depending on the environment, chemical agents can accelerate the crazing rate and decrease the SCG resistance of plastic pipes. These acidic agents in the chemical environment deplete the pipe's antioxidants, weaken craze fibrils, grow through pipe's wall, and deteriorate it chemically.

Ductile cracking, SCG, and RCP are three major types of cracking/rupture in plastic pipes. In ductile fractures, a longer time is needed for rupture to occur, and a proper design can guarantee the prevention of this failure. SCG fracture is a premature failure that happens abruptly with a limited crack length that grows over time. Chemical deterioration and high-stress points lead the pipe into SCG failure. RCP fracture is also an abrupt premature failure, but the crack length can grow up to a couple pipes' length swiftly. SCG is the most common premature failure in plastic pipes. Buckling and deformation of plastic pipes can jeopardize the serviceability of plastic pipes by changing the pipe's cross-section, and as the result of that, applied pressure to pipe wall. It is recommended to have a careful inspection during installation and storage phases to prevent high-stress point as much as possible. The utility companies should be aware of the negative effect of extreme exposure to chlorine in the long run. It can expose the plastic pipeline systems to brittle behavior, and consequently, brittle cracks.

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