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research vs. practice

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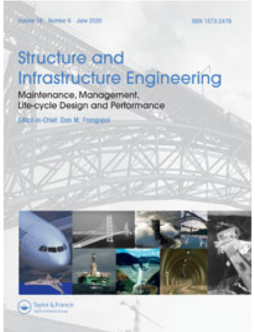

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A review on the durability of PVC sewer pipes: research vs. practice

Konstantinos F. Makris[a], Jeroen Langeveld[a,b] and François H. L. R. Clemens[a,c]

[a]Department of Watermanagement, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands; [b]Partners4UrbanWater, Nijmegen, The Netherlands; [c]Department of Hydraulic Engineering, Deltares, Delft, The Netherlands

ABSTRACT
Polyvinyl chloride (PVC) has become one of the dominant construction materials for sewer systems over the past decades, as a result of its reputed merits. However, since PVC sewer pipes have operated for decades in a hostile environment, concern over their longevity has been lately raised by sewer managers in the Netherlands. Towards that direction, the main factors and mechanisms that affect a PVC pipe's lifetime are discussed in this article, along with the current lifetime prediction methods and their limitations. The review of relevant case studies indicates that material degradation, if any, occurs slowly. However, inspection (CCTV) data of three Dutch municipalities reveals that severe defects have already surfaced and degradation evolves at an unexpected fast rate. A main reason of this gap between literature and practice is the fact that comprehensive material testing of PVC sewer pipes is rarely found in the literature although it proves to be essential in order to trustfully assess the level of degradation and its origins.

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Polyvinyl chloride; plastic pipes; sewers; degradation; ageing; inspection data

Introduction

Plastics are used for a wide range of commercial and industrial piping applications. The most known are polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), acrylonitrile–butadiene–styrene (ABS), polybutylene (PB) and glass–fibre-reinforced polyester (GRP or FRP). Concerning piping systems for drinking water supply, gas distribution and sewage disposal, PVC, PE and PP are the most popular polymer materials (PlasticsEurope, 2017). Especially for gravity sewer pipes, PVC has been extensively used over the past decades and has become the dominant construction material. Cost efficiency, ease of installation, range of available diameters (40–630 mm) and its reputed chemical resistance favour its wide acceptance by decision makers in urban drainage (Davidovski, 2016).

Since there are PVC sewer pipes in operation for at least four decades, concern over their longevity has been lately raised in the Netherlands. It is still unknown whether the expectations of long-lasting PVC pipes (Folkman, 2014) will prove realistic or new asset management strategies should be established in the near future. Knowledge of the current structural integrity of sewer systems is a key issue for establishing successful asset management strategies, leading to better decision making and more affordable investments. In practice, sewer managers currently base their strategies mainly on visual (CCTV) inspections (Van Riel, Langeveld, Herder, & Clemens, 2014). Subsequently, decisions are taken whether replacement, rehabilitation or a near future inspection should take place. However, linking the observed defects in CCTV to the actual physical state of a pipe is challenging (Van Riel, 2017). A necessary condition for achieving this is comprehensive understanding of the mechanisms that affect a PVC pipe's lifetime, their combined effects and eventually their results, which are the defects found in practice. An overview of these mechanisms and their origins is included in this article. Lifetime prediction methods for plastic pipes are also utilised to describe specific types of failure, while their ability to provide trustful lifetime prediction is discussed.

The main aim of this article is to present case studies of PVC sewer pipes found in the literature and to compare the derived conclusions on PVC durability with findings in inspection (CCTV) data. Emphasis is given on the studies that investigate the properties that define the structural integrity and overall performance of a sewer system. The inspection data concerns three different municipalities in The Netherlands: Almere, Amstelveen and Breda. The main discrepancies between literature and inspection data are discussed, as a step towards bridging results from scientific research and observations from practice.

Factors and mechanisms affecting PVC pipes lifetime

From the initial stages of production until the last stages of operational lifetime, several factors exist which could potentially influence the physical, chemical and, hence,

CONTACT Konstantinos F. Makris k.makris@tudelft.nl

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mechanical properties of PVC pipes. An overview of these factors and the observed mechanisms is provided in the following sections.

Production

Suspension polymerisation is the most applied process for PVC particles production (80%), whereas emulsion and mass polymerisation provide 12 and 8% of the world production, respectively (Fischer, Schmitt, Porth, Allsopp, & Vianello, 2014). Although the specific details of the PVC particles size slightly differ in the literature (Benjamin, 1980; Butters, 1982; Faulkner, 1975), the microstructure follows the same pattern. This can be described in three stages (Butters, 1982): the stage III-PVC particle (~100–150 µm), the stage II-primary particle (~0.1–2 µm) and the stage I particle (~10 nm). The conversion of the material to a homogeneous product requires that the boundaries of the primary particles disappear and a new continuous entanglement network is developed (Visser, 2009). This procedure is known as the gelation process and its quality is expressed by the gelation level. There are several methods to obtain information about the gelation level (Castillo, 2016; Choi, Lynch, Rudin, Teh, & Batiste, 1992; Fillot, Hajji, Gauthier, & Masenelli-Varlot, 2006; Gilbert & Vyvoda, 1981; Gramann, Cruz, & Ralston, 2010; Johansson & Törnell, 1986; Kim, Cotterell, & Mai, 1987; Marshall & Birch, 1982; Real, João, Pimenta, & Diogo, 2018; Terselius, Jansson, & Bystedt, 1981; Van der Heuvel, 1982).

A general accepted opinion suggests optimum gelation levels of 60–85% (Benjamin, 1980; Breen, 2006). A temperature of >250 °C is needed for this purpose (Guerrero & Keller, 1981), much higher than the degradation temperature of PVC which is ~205 °C (Wypych, 2015). Due to this fact, thermal energy is complemented with mechanical energy (high shear stresses) by the use of twin rotating screws, so as to accelerate this process without extensive exposure of the material to high temperatures (Visser, 2009). Subsequently, the molten material is introduced in a die so that the final pipe is shaped and cooled. This manufacturing technique is called extrusion and is extensively used to form pipes. Fittings, such as joints, are formed by the injection moulding technique. In the injection moulding process, the melted plastic is injected in a mould, which gives the desired form to the fitting, and after cooling the product is ejected.

During the production process, several additives and fillers may be incorporated in the polymers structure in order to enhance its chemical and physical properties, respectively. Plasticisers and stabilisers are the main additives as they affect the behaviour and degradation rate of the material through its lifecycle. Plasticisers are utilised in order to replace some monomers of the polymer chain, offering a higher degree of mobility and, hence, more flexibility. For sewer applications unplasticised rigid PVC pipes are used. Stabilisers are added for increased resistance to e.g.: UV rays, chemical attack and other relevant external factors (Cardarelli, 2008). For PVC pipes in Europe, lead has been used until the early 2000s, when it was replaced by calcium-based stabilisers in most countries (Anders, 2014).

Table 1. Observed values for circumferential residual stresses in PVC pipes.

DN	Residual stress (MPa) Tensile	Compressive	Reference
–	1.5–4.8	–	Breen (2006)
315	2.6	–	Meerman (2008)
125	2.2	–	
110	1.7	–	
125	1.1	–	
125	1.3	–	
125	2.3	–	
200	0.9		
32	–	5.6–9.4	Scholten et al. (2016)
110	–	3.9–6.6	

Every step within the production of PVC pipes and fittings can have an effect on the long-term performance of the final product. The levels of water and oxygen during polymerisation could influence the formation and quality of the produced PVC particles (Butters, 1982). Subsequently, the gelation process, already affected by the degree of polymerisation (Fujiyama & Kondou, 2004), plays a major role in the mechanical properties (Mandell, Darwish, & McGarry, 1982; Moghri, Garmabi, & Akbarian, 2003; Truss, 1985; Van der Heuvel, 1982). These properties are determined by the morphology of the material (Benjamin, 1980; Kuriyama, Narisawa, Shina, & Kotaki, 1998) and by the polymer's orientation and molecular mobility (Fillot, Hajji, Gauthier, & Masenelli-Varlot, 2007). Additionally, impurities and voids in the polymer structure, frequently referred to as inherent defects, are introduced during production, resulting in crack initiators, and their presence seems to be inevitable (Johansson & Törnell, 1987). The wear observed at the polymer pipes extruders (Gladchenko, Shevelya, Kiyanitsa, & Derkach, 1997) might also contribute to the occurrence of inherent defects.

Residual stresses are also introduced during production, as a result of different cooling rates between the inner and the outer pipe surface (Siegmann, Buchman, & Kenig, 1981), and constitute another parameter that affects the mechanical properties of the produced pipe (Siegmann, Buchman, & Kenig, 1982). Relevant research on residual stresses in PVC pipes (Breen, 2006; Meerman, 2008; Scholten, van der Stok, Gerets, Wenzel, & Boege, 2016) has revealed that their magnitude is in a range of 0.9–4.8 MPa for tensile and 3.9–9.4 for compressive stresses (Table 1). In principle, a faster cooling rate or a thicker pipe wall thickness will lead to higher levels of residual stresses (Janson, 2003; Scholten et al., 2016). However, irrespective of their magnitude, residual stresses affect the crack propagation as they change the stress profile through the pipe (Burn, 1992; Chaoui, Chudnovsky, & Moet, 1987), increase the brittle–ductile temperature (Scholten et al., 2016), and, consequently, they seem to have a tremendous effect on the lifetime of pressurised plastic pipes (Hutař et al., 2013; Poduška et al., 2016).

In the literature, the residual stresses in plastic pipes have been estimated by solely slitting pipe rings approaches and measuring the change in perimetry (Breen, 2006; Janson, 2003; Meerman, 2008), or slitting is combined with layer removal methodologies (Doshi, 1989; Poduška et al., 2014, 2016; Williams, Hodgkinson, & Gray, 1981) in order to acquire a more accurate distribution of the residual stresses through the pipe thickness.

The values of residual stresses listed in Table 1 are estimated based on Equation (1) for tensile residual stresses (Breen, 2006) and Equation (2) for compressive residual stresses (Janson, 2003):

$$\sigma = \frac{l_o \cdot d}{4 \cdot \pi \cdot R^2} \cdot E \tag{1}$$

where l_o is the overlap length, d is the wall thickness, R is the mean radius of the pipe wall and E is the modulus of elasticity:

$$\sigma = \frac{a}{\pi \cdot D_m - a} \cdot \frac{s}{D_m} \cdot E \tag{2}$$

where a is the reduction of the pipe perimetry, s is the pipe wall thickness, D_m is the mean pipe diameter and E is the creep or relaxation modulus of the pipe. The description of E modulus in the equations of this article is kept as in the original sources. However, in viscoelastic materials (a.o. PVC), E is described as creep or relaxation modulus, since it is a function of loading time.

Installation

The conventional installation procedure involves the digging of an open trench, lying of the pipe and soil covering and compaction. However, during transport and installation of plastic pipes, scratches and dents can be inflicted on the pipe surface. These plastic deformations can later act as stress risers, and under certain service conditions can eventually lead to failure. Improper soil compaction is also the cause of pipe ovalisation, resulting in high tensile stresses at the 12 and 6 o' clock positions of the inner surface and at the 3 and 9 o' clock positions of the outer surface. In pressurised systems, homogeneous soil embedding can exert external pressure on the pipe, counteracting the internal pressure and hence reducing the probability of crack formation (Hutař et al., 2011).

Additionally, poor quality of soil embedding could amplify the effects of the low bending stiffness found in plastic pipes, resulting in improper and challenging to measure longitudinal slopes in gravity systems, and in pre-buckling conditions (Stein, 2001). Another factor that can affect the material degradation is determined by the conditions of storage prior to installation. Photochemical degradation caused by UV rays has been proven to be harmful for the mechanical properties of PVC pipes (Anton-Prinet, Mur, Gay, Audouin, & Verdu, 1999; Hussain, Hamid, & Khan, 1995).

Operation

During operation, four main ageing mechanisms have been identified: physical ageing, mechanical degradation, chemical degradation and environmental stress cracking (ESC). Physical ageing in polymers is a phenomenon which imposes changes on a material's property as a function of time, at a constant temperature and independently of other external factors (Hutchinson, 1995). Amorphous (or glassy) polymers, such as PVC, experience physical ageing due to the fact that they are cooled to a temperature below their glass transition temperature (T_g), and, hence, are not in a thermodynamic equilibrium state. In this non-equilibrium state, the glassy polymer has excessive thermodynamic properties and there is a continuous effort to reach the equilibrium state (Hutchinson, 1995). Physical ageing can be traced by reduction in volume and enthalpy, but also by changes in the mechanical properties (Rabinovitch & Summers, 1992). The polymer becomes stiffer and more brittle, whereas its creep and stress relaxation rates decrease (Laiarinandrasana, Gaudichet, Oberti, & Devilliers, 2011; Struik, 1977). In principle, physical ageing is an inevitable, although reversible (Hutchinson, 1995), process in polymers which is accelerated at higher temperatures (Visser, Bor, Wolters, Warnet, & Govaert, 2011).

Mechanical degradation is the result of stresses which are exerted on the pipe (or joint) and their level surpasses the material's fracture threshold. It appears in the form of fissures (crazes, cracks) or breaks. Stresses originate from internal pressure, deflections due to soil cover, and the production process (residual stresses). Additional stresses can be imposed by axial bending due to improper soil bedding and compaction. The quality of pipe extrusion can be a decisive factor for the longevity of the pipe, as crack initiation is observed in built-in voids and impurities. Subsequently, the propagation of the crack is governed by the magnitude and direction of the applied stresses. This failure mechanism is known as Slow Crack Growth (SCG). In case of external impacts (e.g. hit by an excavator), mechanical degradation could surface as rapid crack propagation. Apart from processing quality, temperature is also a critical factor concerning the mechanical properties of the material. Lower temperatures result in more brittle failures, whereas the amount of energy that can be absorbed by PVC pipes before fracture seems to reduce dramatically (McGarry, Mandell, & Hsueh-Lee, 1985; Scholten et al., 2016; Visser et al., 2011).

Chemical degradation involves the occurrence of chemical reactions between the polymer pipe and the environment, leading to breakage of the polymer covalent bonds. The covalent bonds build up the main back bone of a polymer chain, hence their breakage results in chain scission and molecular weight reduction. Dehydrochlorination (HCl abstraction) is often the cause that commences chemical degradation in PVC (Breen, 2006), due to the creation of sequential conjugated polyenes (Arnold, 2003), which is also the source of the discolourisation appearance. The impact on the mechanical properties has been characterised with the term 'stress corrosion cracking', and is realised in four stages (Choi et al., 2005): initiation of microcracks, slow crack growth, clustering of cracks and clusters growth.

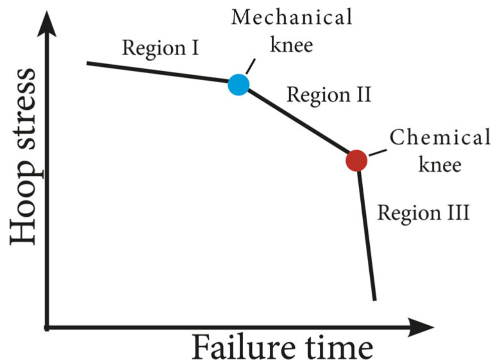

Figure 1. The types of failures observed in thermoplastic pipes subjected to various levels of hoop stress.

Environmental stress cracking is a failure mechanism very similar to slow crack growth in terms of shape. It is a physical process driven by the applied stress but accelerated by the presence of an active environment (Bishop, Isaac, Hinksman, & Morrissey, 2000), as diffusion is the factor that enhances the susceptibility to fractures due to the creation of plasticised (softer) layers and surface energy reduction (Arnold, 2003). Breen (1993, 1994, 1995) has explored crazing and crack growth mechanisms concerning PVC pipes in vapour and liquid environments, concluding that above a certain level of environment concentration and stress intensity, the material's load-bearing capacity can decrease. In general, a wide range of glassy polymers (including PVC) has been investigated regarding their ESC resistance under various types of environments (Robeson, 2013), indicating that issues of ESC may appear in certain combinations of 'material-environment'.

Lifetime prediction methods and their limitations

Hydrostatic testing and standard extrapolation method

A conventional way of rating a thermoplastic pipe is by determining the resistance to constant internal pressure, as it is described in ISO 1167-1 (2006). The experiments are implemented under several internal pressures and temperatures, and under certain environmental conditions (i.e. water in water, water in air, water in liquid). The time to failure is recorded and the results are depicted as a double logarithmic σ_{hoop} vs. $t_{failure}$ curve. An incident of failure is considered when there is leak or break. The type of failure can be ductile (Region I), quasi-brittle (Region II) or brittle (Region III).

Figure 1 shows how the level of applied stress leads to one of the three types of failure as a function of time. In case of high stress values (Region I), a yield deformation in the failure zone is vivid with fracture appearing within short testing times. For intermediate stress levels (Region II), the failure is generated in longer testing times and is characterised by slow crack growth with local plastic deformation only at the crack front. In even longer testing durations (Region III), there is no apparent yield deformation and the occurrence of fractures is nearly independent of the stress level. The points of transition from Region I to II and from II to III are frequently referred to as the 'mechanical knee' and the 'chemical knee', respectively.

Higher testing temperatures tend to move the curves to lower failure times, allowing for shortest testing periods. This is apparent in Figure 2, in which the maximum level of hoop stress as a function of time and temperature is presented for unplasticised PVC pipes. Extrapolation to service temperatures can then be performed according to the standard extrapolation method (SEM) published in ISO 9080 (2012). Standard extrapolation method requires extensive hydrostatic testing at two or more testing temperatures (>30 samples per temperature) and the application of certain statistical methods to the obtained experimental data sets.

One apparent limitation of performing hydrostatic pressure tests is the necessary duration of the experiments. The relevant standardised guidelines (ISO 1167-1, 2006; ISO 9080, 2012) indicate that the applied internal pressures should be at such levels that at least four specimens would fail after 7000 h (292 days) and at least one after 9000 h (375 days). This fact could justify that this kind of method has been used only by a few researchers and usually partially, in order to avoid the extensive testing required by SEM. A case of full implementation of this method has been published by Krishnaswamy (2005), who tested eight different kinds of HDPE pipe resins. Other reported limitations originate from the thermal ageing involved in this method. Sorption and diffusion of oxygen or other chemicals in the polymer matrix are temperature-dependent micro-mechanisms contributing to the failure process (Lang, Stern, & Doerner, 1997). However, SEM lacks in incorporating the variability of different temperature-dependent rates introduced by different physical and chemical processes.

Arrhenius equation

Application of the Arrhenius equation is considered feasible under the assumption that the degradation rate of the material follows a first-order kinetics. It is a method highly connected with the chemical aspects involved in the degradation process, indicating the depletion of the introduced stabilisers and the onset of thermo-oxidative degradation (Figure 1, Region III). These aspects are usually expressed via the reduction of the oxidation induction time or the build-up of hydroperoxides (ROOH).

The concept behind this method is also higher testing temperatures and shorter testing periods. Subsequently, the Arrhenius model is used for extrapolation of the rate of degradation reaction (k) to other (service) temperatures, allowing for lifetime prediction:

$$\ln k = -\frac{E_a}{R}\frac{1}{T} + \ln C \tag{3}$$

where k is the degradation reaction rate, E_a is the activation energy of the reaction (kJ/mol), R is the gas constant (8.31 $JK^{-1}mol^{-1}$), T is the testing temperature (K) and C is a constant.

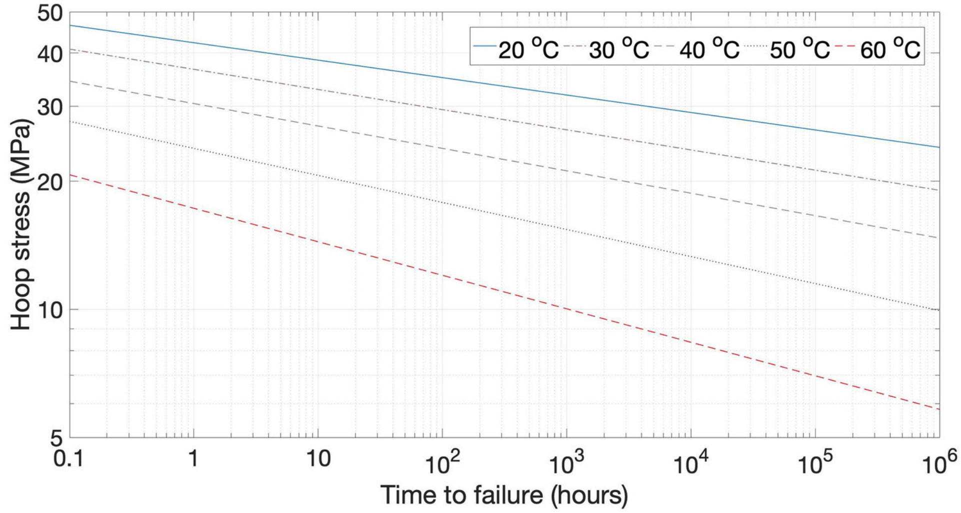

Figure 2. Maximum hoop stress (MPa) with respect to time (hours) for various temperatures concerning PVC-U pipes. Data is retrieved from Kunststoffrohrverband (1997).

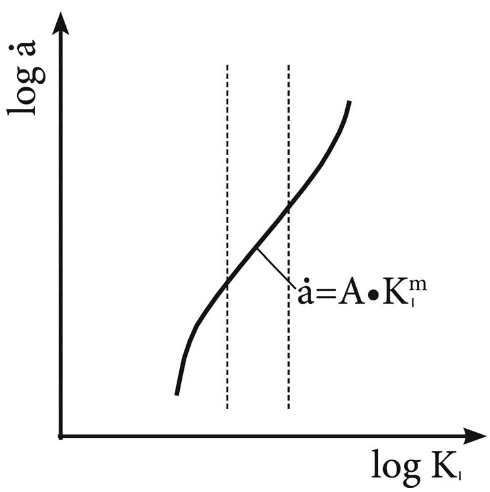

Figure 3. Creep crack growth rate as a function of stress intensity factor K_I.

The assumed linearity involved in the Arrhenius model seems, however, to be valid only for a range of testing temperatures (Celina, Gillen, & Assink, 2005). This fact indicates that caution should also be exercised for the use of the extrapolation factors k_e which are included in ISO 9080 and concern lifetime prediction in case of Region III failure based on the Arrhenius linearity. For instance, relevant research on PP (Celina et al., 2005) has shown that at circa 80 °C the degradation rate of PP seems to lose its Arrhenius linearity. Generally, thermo-oxidative degradation based on accelerated ageing experiments is a more complicated mechanism that depends on the physics involved in the process (e.g. diffusion), and the behaviour of the present stabilisers and other additives (Celina, 2013).

Linear elastic fracture mechanics

Numerous researchers have focused on simulating slow crack growth (Figure 1, Region II) which originates from inherent flaws and is propagated by the applied stresses. The applied stresses are expressed via the stress intensity factor K_I, which considers the internal pressure, the pipe and crack geometrical characteristics, and the type of loading (Maiti, 2015). K_I corresponds to the mode I type of loading which indicates tension of the pipe in a direction perpendicular to the plane of the crack.

The time of crack initiation can be expressed via (Lang et al., 1997):

$$t_{in} = B \cdot K_I^{-n} \tag{4}$$

As shown in Figure 3, when the crack growth rate da/dt (or $\dot{a}$) is plotted against the stress intensity factor K_I in a double logarithmic scale, Equation (5) can be established for a specific range of da/dt in order to describe slow crack growth. Prior to this phase, crack growth rate decreases rapidly as the threshold value $K_{I\text{th}}$ is approached, whereas at the end it increases rapidly as the material's fracture toughness K_{IC} is approached:

$$\frac{da}{dt} = A \cdot K_I^m \tag{5}$$

B, n and A, m used in Equations (4) and (5), respectively, are sets of constants which depend on the tested material.

The lifetime prediction can be accomplished by estimating the crack initiation time according to Equation (4) and integrating Equation (5) for the stable crack growth period:

$$t_f = t_{in} + t_{SCG} = B \cdot K_I^{-n} + \int_{a_o}^{a_f} \frac{da}{A \cdot (K_I)^m} \tag{6}$$

where a_o is the assumed initial flaw size and a_f is the critical crack size which is usually assumed to be the pipe wall thickness. Most of the authors, however, tend to neglect the initiation time t_{in} as separate experiments are needed for the determination of B and n, and it is considered negligible compared to the magnitude of t_{SCG}.

This lifetime prediction model has been the basis for extensive research on PE pipes (Deveci & Fang, 2017; Frank, Freimann, Pinter, & Lang, 2009; Frank, Hutař, & Pinter, 2012; Kratochvilla, Frank, & Pinter, 2014; Pinter, Lang, & Haager, 2007; Wee & Choi, 2016; Zhao, Choi, &

Chudnovsky, 2013), PVC pipes (Balika & Lang, 2002; Gould, Davis, Beale, & Marlow, 2013) and elastomers (Arbeiter, Schrittesser, Frank, Berer, & Pinter, 2015). The types of specimens used in such experiments are usually the cracked round bars or circular notched specimens. Other types of experiments include specimens for the Pennsylvania notched test (Brown, 2007; Nezbedová et al., 2013; Robledo, Domínguez, & García-Muñoz, 2017) and the strain hardening test (Deveci & Fang, 2017; Robledo et al., 2017).

Linear elastic fracture mechanics (LEFM) method is based on short-term (mainly fatigue) tests and focuses on describing the fracture mechanisms (i.e. slow crack growth) at the crack tip. This fact implies that other types of degradation, such as chemical, which may occur in a plastic pipe should be restricted in the area of the crack tip. Otherwise, slow crack growth is no longer the critical factor for the pipe's failure, and the application of the LEFM method in its conventional form seems to be invalid. Another limitation in applying the LEFM method is the requirement for input of the precise geometry (size and shape) of the initial defect. Analysis of the uncertainties that are introduced in modeling slow crack growth by means of LEFM for PVC (Davis, Burn, Moglia, & Gould, 2007) and HDPE (Khelif, Chateauneuf, & Chaoui, 2007) emphasised the significance of inherent defect sizes in the reliability of the model's outcome. Other researchers (Burn, 1991; Lu, Davis, & Burn, 2003) have also commented on the sensitivity of the estimated lifetime prediction to the initial flaw geometry. According to the literature, initial defect sizes of 100–400 μm seem to be realistic (Lang et al., 1997).

Quality number

The quality number method was applied for plastic pipes solely by Whittle and Tennakoon (2005), according to the authors' knowledge. It considers the properties that affect the durability of the system and their respective weighting factors in a cumulative form (Equation (7)). Lifetime prediction is made by applying Equation (7) on several pipes of different ages and creating a simple linear regression with the pipe age as the independent variable. Subsequently, extrapolation is feasible to longer ages until a threshold quality number is reached, below which a pipe is considered to be unsafe for further operation. The age which corresponds at the threshold is considered as the predicted lifetime:

$$Q = \sum_{i=1}^{n} W_i \frac{M_i}{R_i} \tag{7}$$

where Q is the total quality number, W_i is the weighting factor of a property, M_i is the measured value of a property and R_i the reference value of a property.

It is reasonable to state that the results obtained by this method are certainly open to dispute. This is due to the fact that the outcome is dependent on the arbitrary choice of the weighting factors and the threshold quality number, rising the levels of uncertainty. Additional caution should also be exercised when applying this method as it implies a connection between the age and the integrity of the pipe, irrespective of the quality of production. However, older pipes which are more well processed than newer pipes could provide higher values of Q, leading to a regression model with positive slope. This fact would result in the poorly founded conclusion that failure will never occur.

PVC pipes in literature

Material properties

A moderate amount of research is published concerning PVC sewer pipes, which are either new or used for several years, and have been utilised in different areas. Table 2 provides an overview of specifications of the tested exhumed pipes. An early study (Bauer, 1990) was conducted on a 15-year old PVC sewer pipe (DN 254, SDR 35) in Dallas, Texas, based on the requirements imposed by ASTM D 3034. Measurements of the tensile properties showed a mean tensile strength of 52.36 MPa and mean modulus of 2839 MPa in the circumferential direction and 55.4 and 3059 MPa, respectively, in the longitudinal direction. The average pipe stiffness was reported to be 433 kPa according to ASTM D 2412-11. A series of other tests following the respective American standards took place, including extrusion and installation quality, dimensions measurement, impact resistance and flattening resistance. According to the study, the results revealed that all the measured properties comply with ASTM D 3034 and no observable degradation had occurred.

Similar studies in Europe (Alferink, Guldback, & Grootook, 1995; Meerman, 2008) include the investigation of several PVC sewer pipes of different SDRs and ages (Table 2). A lot of emphasis has been given to deflection measurements and production or installation practices. However, there is no extensive exploration of mechanical properties and their potential deterioration. The only case concerns two PVC pipes from Norway (Notteroy) and Sweden (Torshalla), whose properties have been compared with a brand-new pipe. The results (Table 3) indicate that the properties of the pipes have been compromised. The pipe tested from Norway, which is of the same diameter but of lower pipe wall thickness (higher SDR value) compared to the reference pipe, indicate only a slight decrease of 16.8% in strain at break, whereas the yield stress remains intact. Concerning the pipe from Sweden, the results revealed a 7.8% decrease in yield stress and 80.6% decrease in strain at break, a fact which may be explained by the low degree of gelation. A contributing factor to the decrease in the strain at break is also physical ageing although an increase in yield stresses was expected.

In this study, the degree of gelation was expressed as a percentage of attack of methylene on PVC. Based on the provided values for all pipes, it is obvious that the majority of the pipes seem to be of poor production quality, i.e. low degree of gelation. In the Netherlands the case of seven exhumed PVC sewer pipes has been reported (Meerman, 2008). The level of degradation of these pipes was evaluated based on visual and microscopic inspection, geometrical

Table 2. Overview of tested PVC sewer pipes.

Reference	Location	Age (years)	DN	SDR	Testing method/tested property
Bauer (1990)	Texas	15	254	35	Acetone immersion, dimensions, flattening, impact resistance, joint tightness, pipe stiffness, tensile properties and workmanship
Alferink et al. (1995)	France	12	315	41	Dimensions and pipe stiffness
		25	200	51	Dimensions, Fourier transform infrared spectroscopy (FTIR), joints tightness, methylene chloride test (MCT), pipe stiffness and X-ray fluorescent (XRF)
		23	315	51	
		25	400	41	
	Denmark	23	160	41	
		30	200	34	
		28	200	41	
	Norway	22	250	51	Dimensions, Fourier transform infrared spectroscopy (FTIR), joints tightness, methylene chloride test (MCT), pipe stiffness, tensile properties and X-ray fluorescent (XRF)
	Sweden	24	200	41	
Whittle and Tennakoon (2005)	Australia	25	150	38	Differential scanning calorimetry (DSC), impact resistance, pipe stiffness, joints tightness, specific gravity and tensile properties
			150		
		16	150		
			150		
		11	225		
			225		
		20	150		
Meerman (2008)	The Netherlands	35	315	34	Dimensions, microscopic inspection, residual stresses, surface roughness and visual assessment
		Up to 25	110		
			125		
			125		
			125		
			125		
			200	51	
Gould et al. (2013)	Australia	34	200	~20 (PN12)	Attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR), scanning electron microscope (SEM) with energy dispersive X-ray spectrometer (EDS)
Folkman (2014)	USA	20	610	18	Acetone immersion, dimensions and hydrostatic integrity

Table 3. Material properties of 10 PVC sewer pipes in France, Denmark and Norway (Alferink et al., 1995).

Place	DN	SDR	Age (years)	Percentage of attack (%)	Yield stress (MPa)	Strain at break (%)
Gerzat	200	51	25	No attack	–	–
Montpellier	315	51	23	25–30	–	–
St. Agathe	400	41	25	100–100	–	–
Courchevel	315	41	12	–	–	–
Odense	160	41	23	75–100	–	–
Nykobing	200	34	30	65–100	–	–
Nykobing	200	41	28	25–90	–	–
Notteroy	250	51	22	35–100	50	142
Torshalla	200	41	24	50–100	46.1	33
Reference	250	41	New	No attack	50	170

Table 4. Material properties of 7 PVC sewer pipes in the Netherlands (Meerman, 2008).

DN	Age (years)	Circularity (D_{max}/D_{min})	Microscopic/visual Assessment: Inner	Microscopic/visual Assessment: Outer	Roughness (μm)
315	35	1.02	Scratches, wear and crazes	Discolouration and scratches	–
125	Up to 25	1.01	Scratches, wear, crazes and discoloration	Slight discolouration and scratches	1.0
110		1.03	Wear and discoloration	Scratches	0.9
125		1.02	Moderate wear	Scratches	0.4
125		1.01	Wear and discoloration	Strong discolouration and scratches	0.4
125		1.05	Crazes	Moderate discolouration and scratches	0.3
200		1.02	Scratches and wear	Scratches	0.6

analysis and surface roughness measurements (Table 4). Comprehensive testing on the pipe's properties did not take place, and the suggestion of at least 100 years lifetime was based on a previous report on PVC water pipes (Breen, 2006). It has to be realised that in drinking water pipes the environment is totally different and chemical degradation or ESC as failure mechanism is neglected.

The results of a more comprehensive, in terms of mechanical properties, study (Whittle & Tennakoon, 2005) of seven PVC sewer pipes that had served for up to 25 years in Australia are summarised in Table 5. These properties were also combined with the production process conditions. In this case study, the degree of gelation is expressed as the gelation level, determined by means of differential scanning calorimetry. As it is indicated by the results, there is no actual connection between the age, the gelation level and the mechanical properties of the tested pipes. In fact, the pipe with the lowest gelation level (35%) correspond to the highest magnitudes of stress (39.3 MPa) and elongation (117.2%) at break. At the same time, pipes with optimum gelation levels (76–88%)

Table 5. Material properties of seven PVC SDR38 sewer pipes in Australia (Whittle & Tennakoon, 2005).

DN	Age (years)	Gelation level (%)	Processing temperature (°C)	Ring stiffness (N/m/m)	Yield stress (MPa)	Stress at break (MPa)	Elongation at break (%)	Impact result[a]
150	25	43	172	6.047	42.2	37.8	18.3	Brittle (4)
150	25	59	173	5.905	43.2	37.9	28.9	Brittle (1)/No fracture (1)
150	16	46	173	7.309	43.9	38.9	84.5	Brittle (1)/No fracture (3)
150	16	35	173	6.834	43.0	39.3	117.2	Brittle (3)
225	11	88	182	7.785	39.1	34.9	56.5	Brittle (2)/No fracture (4)
225	11	76	181	8.759	39.4	34.9	79.4	Brittle (6)/No fracture (4)
150	20	73	175	10.350	41.7	36.3	63.8	Brittle (2)/No fracture (10)

[a]The number of tested specimens is in parenthesis.

Table 6. Approximate deflection values of PVC sewer pipes 7.5 years after installation as a function of SDR, compaction quality and soil cover (Välimaa, 1982).

SDR	Compaction	Soil cover (m)	Deflection (%)
51	Light vibration	0.6	3.1
51	Treading	0.9	2.1
51	Heavy vibration	1.2	0.3
34	Treading	0.6	2.6
34	Heavy vibration	0.9	1.6
34	Light vibration	1.2	0.9

correspond to the lowest magnitudes of yield stress and tensile strength. A valid argument provided by the researchers of this study is that higher concentrations of fillers, expressed as an increase in specific gravity (i.e. from 1.465 for DN 150 to 1.522 for DN 225) could have led to this discrepancy. Finally, application of the quality number method (Equation (5)) yields proposed lifetimes of 98–288 years based on a worst-case and best-case scenario, respectively.

Pipe stiffness is considered as the main design property in gravity sewer pipes. This fact has led some research approaches to focus on the mechanisms and properties of plastic sewers which are considered to be connected with pipe stiffness, such as deflection and stress relaxation. The deflection of a flexible pipe is a function of several parameters. Pipe material and geometrical characteristics, the bedding and backfilling material, the compaction degree, the burial depth and the existence of geogrid reinforcement could change the levels of deflections significantly (Hsieh, Wu, & Huang, 2010; Mohamedzein & Al-Aghbari, 2016; Välimaa, 1982). Irrespective of potential structural deterioration, pipe deflections in sewer pipes have a profound impact on significant operational and asset management aspects, such as the flow regime (Stein, 2001) and the cost of future trenchless rehabilitation (Kuliczkowska, 2014) respectively.

The results of deflection measuring programmes regarding PVC sewer pipes in several countries are summarised in Table A1. In Europe, deformations of up to 14% were observed (Alferink et al., 1995; Välimaa, 1982; Walton & Elzink, 1989). The magnitudes of these values are in accordance with the values observed in the United States (Moser, Shupe, & Bishop, 1990). Observation of the temporal alterations of these values with respect to time since installation justifies that 90–95% of total deflection is realised within the first 2 years (Joekes & Elzink, 1985). This period is also considered sufficient to account for soil consolidation due to groundwater fluctuations (Moser et al., 1990). In-situ deflection measurements reported by Kuliczkowska (2014) on approximately 3.5 km of newly layed PVC sewer pipes of several diameters (200–500 mm) confirm that similar deflection values (up to 15%) can be obtained even at the first stages after installation, whereas the vast majority of the tested pipes (95%) were subjected to deflections between 2 and 10%. Other research (Alferink et al., 1995) has also highlighted the importance of installation quality. Moderate installation yields magnitudes of mean deflection up to 5.5%, whereas poor installation results in mean deflections of up to 13% and maximum deflections up to 20.5%.

The impact of pipe stiffness (expressed as SDR) on the performance of an operating pipe has been explored (Välimaa, 1982) via an elaborated field test of six PVC pipes with variations in pipe stiffness, soil cover and compaction method. By the end of the testing period (i.e. 7.5 years), at which the deflection levels are considered to be stable, soil cover appears to be the most dominant factor (Table 6). At 1.2 m depth, the pipe of lower pipe stiffness with better soil compaction was less deflected than the pipe of higher stiffness. At 0.6 m depth pipe stiffness played a more significant role than the compaction method. Hence, pipe stiffness seems to be more important in low depths, whereas in high soil covers the compaction method becomes more significant.

Stress relaxation in PVC sewer pipes has been extensively studied by Struik (1977) and Janson (1988, 1995, 2003). It is proved that under constant deflection, stress decreases implying that modulus E decreases. Viscoelasticity causes a stress relaxation state which indicates that if failure does not occur during the initial loading, it is very unlike that failure in the long term will occur as the applied stress will continuously decline.

However, this decrease in the modulus should not be translated as a decline in the strength of the pipe as the short-term value of the modulus remains intact, or is even enhanced as a result of physical ageing (Janson, 1995, 2003). This has generated a confusion among researchers as to whether the long-term (Hsieh et al., 2010; Janson, 1988; Koski, 1982) or short-term (Janson, 1995, 2003; Moser et al., 1990) value of modulus should be used to describe pipe stiffness (Equation (12)). Janson (1995) argues that whether the short-term or long-term stiffness should be considered depends on the type of soil and the impact it has on the behaviour of the pipe. Therefore, for sandy soils the use of short-term stiffness is appropriate, whereas for plastic soils the long-term stiffness is. Concerning this dispute, Moser et al. (1990) presented the results of the pipe stiffness of PVC pipe samples that had been constantly strained for 13 years under testing conditions. The pipe stiffness was determined after 1 h of the initial imposed deflection (5 and 25%), and was compared to the pipe stiffness measured after 13 years by imposing additional deflection of 5%. The pipes proved to be capable of withstanding additional deflections, which is in accordance with the final findings of Janson (2003). Finally, the influence of fillers and notches on pipe stiffness has also been investigated (Moser et al., 1990), but hardly any significant differences appeared compared to the un-notched or unfilled segments, respectively.

The vast majority of research in the literature concerns plastic sewer pipes that operate under gravity in which the applied stresses are limited to the effect of pipe–soil interactions. In contrast, there is a scarcity on research regarding pressurised plastic sewer systems. According to the authors' knowledge, only two such case studies have been reported (Folkman, 2014; Gould et al., 2013). Therefore, cases of conducted research on pressurised PVC pipes for other applications, which could apply for sewer systems, are also addressed hereafter. At this point, it has to be stressed that the operation of sewer pressurised systems is not governed by a steady internal pressure (creep) as in gas and water systems, but by a cyclic pressure pattern (fatigue). However, the failure mechanism of slow crack growth remains the same in both cases (Hu, Summers, Hiltner, & Baer, 2003).

A recent investigation (Folkman, 2014) of a 20-year-old pressurised PVC sewer pipe took place in the United States. The pipe successfully passed the tests of hydrostatic integrity and acetone immersion. A more detailed study on a failed 34 years old rising main sewer PVC pipe in Australia has been published (Gould et al., 2013). In order to assess the failure cause, a series of methods based on micro-scale examination (SEM) and fractography (FT-IR and EDS) have been applied. The conclusion was that an inherent inclusion created during the manufacturing process served as a stress riser and resulted in crack initiation and eventual failure. In fact, EDS during SEM indicated that iron (Fe) elements were found in the revealed inclusions, implying a low-quality manufacturing process. However, no material degradation due to the contact with sewage was detected although the crack seems to have initiated in the area of the pipe where discolorisation is most profound.

Apart from inherent defects, notches caused during installation could also affect the performance of the pipe. Towards this direction, Burn (1991) explored the effect of notches on PVC pipes which are subjected to cyclic pressure. The experiments included PVC pipes of certain specifications (DN110, class 20, AS 2977) tested at a cyclic pressure of 1.2 ± 0.3 MPa at a frequency of 0.5 Hz. The results revealed that notch depths above a certain level could reduce the lifetime of a pipe drastically. For the given pipe, a notch of >1.2 mm increases the failure probability when subjected to 1.7 million cycles (resembling 100 years lifetime for Australian operating conditions).

Finally, the response of thermoplastic pipes (including PVC) under two cases of combined loading has been investigated (Alferink, Janson, & Wolters, 2004); i) internal pressure and deflection and ii) internal pressure and axial bending. The results revealed that external loads in fact enhance the performance of the pressurised pipe and the bending stresses relax in time. However, failure due to excessive axial bending has been recorded (Broutman, Duvall, & So, 1990) concerning two PVC (SDR 26) water pipes.

Chemical resistance

The materials used for the production of thermoplastic pipes, which are destined for fluid conveyance applications, are generally considered as chemically resistant. Especially, PVC is thought to be the most resistant material against both chemical degradation and abrasion, a fact which explains its massive use in sewer systems. An important issue for both drinking and wastewater plastic pipes is the existence of certain disinfectants in drinking water. Their influence on PVC pipes was studied extensively by Fumire (2008). Static tensile and dehydrochlorination tests, combined by molecular weight measurements and SEM examinations, took place before and after exposure to some common water disinfectants, i.e., sodium hypochlorine–dichlorine ($NaClO–Cl_2$) and chlorine dioxide (ClO_2). Even concentrations of 8 ppm of such disinfectants at 40 °C did not manage to impose significant changes on the material. Indeed, according to other studies (Kowalska, Klepka, & Kowalski, 2016; Kowalska, Rudawska, & Kowalski, 2014), the added chlorine atoms that derive from chlorinated water are considered as a possible reason for a slight increase in the mechanical properties of PVC.

Similar studies have been published for the performance of polyethylene pipes against chlorine-based solutions (Castagnetti, Mammano, & Dragoni, 2011; Ghabeche, Alimi, & Chaoui, 2015; Hassinen, Lundbäck, Ifwarson, & Gedde, 2004; Yu et al., 2011). In these cases, the amorphous part of polyethylene proved to be very sensitive especially to chlorine dioxide and hydrochloric acid, followed by rapid depletion of antioxidants and an increase in crystallinity. The outcome of the mentioned studies indicates the overall superiority of PVC over PE concerning chemical resistance to frequently utilised disinfectants. This trend comes partially in contrast with the findings of the comparative research conducted by Kowalska et al. (2016), as chemical changes at the material surface seem to be more profound in PVC than HDPE pipes, albeit the mechanical properties are not affected in both materials.

Earlier relevant research on PVC also confirmed its chemical resistance. Bishop (1990) introduced a test method for estimating the pipe stiffness of PVC samples, while subjected to constant deflections of 5–10%, and 5% concentration of sulphuric acid (H_2SO_4) or sodium hydroxide (NaOH). After testing periods of more than 1 year, the results revealed negligible effects on the pipe stiffness. The resistance of PVC against sulphuric acid was also verified in another study (Hawkins & Mass, 1994), in which calcium carbonate ($CaCO_3$)-filled PVC sewer pipes were investigated by means of SEM and wavelength dispersive X-ray (WDS) analysis. The pipe samples were exposed to H_2SO_4 (20%) for testing periods up to 6 months. The PVC matrix proved

Table 7. Tensile strength and elongation at break of PVC specimens aged in H_2SO_4 (Lasfar et al., 2014).

Immersion time (h)	Tensile strength at 25 °C (MPa)	Elongation at break at 25 °C (%)	Immersion time (h)	Tensile strength at 40 °C (MPa)	Elongation at break at 40 °C (%)
0	42.58	126.2	0	42.58	126.2
840	49.4	120.3	504	49.97	33.93
1344	48.03	115.85	1200	51.9	30.1
2208	49.6	108.73	1704	52.47	22.5
3048	52.27	83.33	2040	54.17	18.5
4368	56.9	74.81	2208	48.8	18.1

Table 8. Critical deflection values that commenced leakage under testing (Meijering et al., 2004).

Pipe	DN	Age	Sealing material	Critical deflection (%)
PVC SDR41	110	30	SBR	44
		–	SBR	81
		17	NBR	74
		22	NBR	36
		23	NBR	50
		23	NBR	64

to be very resistant as $CaCO_3$ reacted with H_2SO_4 only at the surface of the material.

Finally, a comparative research on the chemical resistance of PVC, PE and PP to sulphuric acid and sodium sulphate (Na_2SO_4) at 25 and 40 °C has been published (Lasfar et al., 2014). The research included measurements of the tensile strength and elongation at break for several durations of immersion. According to the results (Table 7), tensile strength was enhanced whereas the elongation at break was reduced, implying an increase in crystallinity and diffusion of the environment in the material, but no chemical degradation.

Elastomeric joints

There are several types of thermoplastic pipes jointing, including mechanical and welding techniques (Headford, 1998; Stokes, 1989). The most common types of joints in sewer systems are the push-fit, i.e. bell and spigot, and double socket joints. Developments of the conventional push-fit joints can be found, such as the Rieber joint (Magnusson, 1982; Rahman & Bird, 2006).

Some researchers have focused exclusively on the performance of the joints in plastic pipe systems. Meijering, Wolters, and Hermkens (2004) studied double socket joints that had been for up to 30 years in service of PVC gas-distribution systems. The assessment of the joints condition was made based on leak tightness testing under deflection, compression set estimation and determination of basic mechanical properties. Leakage was observed only for pipe deflections over 36%, whereas in one case the critical deflection reached the level of 81% (Table 8). The compression set was measured in an approximate range between 15 and 50%.

Arsénio (2013) also concluded that only extreme bending angles (above 10°) or complete pull-off of the pipe could lead to leakage at the joints regarding drinking water systems. In terms of leak tightness in elastomeric joints, the failure modes that can be observed in push-fit joints are listed and described in detail in Arsénio, Vreeburg, Pieterse-Quirijns, and Rosenthal (2009). Namely, these are joint bending, vertical displacement, horizontal displacement, pipe bending, axial displacement, torsion by slight rotation/vibration and pipe ovalisation. The standardised methods and conditions used to test the leak tightness of joints in gravity flow applications are presented in NEN 1277 (2003), and are discussed and assessed by García, Cortés-Pérez, and Moore (2016).

Bauer (1990) and Meerman (2008) commented on the excessively good quality of the elastomeric seals of exhumed PVC sewer pipes (Table 2), albeit their conclusions were drawn only by visual inspection. In the mentioned studies, the effects of potential microbiological attack on the sealing material have not been investigated. Other researchers have focused on the performance of elastomeric joints towards root intrusion, considering the interfacial pressure as a critical factor. Whittle and Tennakoon (2005) investigated the interface pressure of seven PVC sewer pipes and it was concluded that only two comply with the requirements provided by the relative Australian Standards (AS 1260-1984) and Hunt (1979), which recommend pressure interface higher than 0.55 MPa for 7 mm of continuous width.

Similarly, Sadler, Burn, and Whittle (2001) tested 22 joints (slip-coupling and lip-seal) used in PVC sewer pipes. After 29 months of accelerated root intrusion testing, it was concluded that for interfacial pressures of 0.04–0.20 MPa, root intrusion is likely to occur, but the values of interfacial pressures suggested by AS 1260-1984 are very restrictive and could lead to ring removal and installation difficulties. The detailed experimental setup is described in Lu, Burn, and Whittle (2000), which includes preliminary tests regarding elastomeric joints of PVC, vitrified clay (VC) and fibre-reinforced concrete (FRC) pipes.

The superiority of PVC compared to VC and FRC was finally reported by Whittle (2003), claiming that the surface roughness and porosity of the latter materials were the main cause of root intrusion through the sealing joints. Scharwächter (2001) also assessed the magnitude of sealing forces that must be applied for achieving long-term tight joints in non-pressure systems. By applying method 4 of WG13 (TC 155/CEN), it was concluded that a long-term (considering the relaxation of the elastomer) sealing force of 3–4 N/mm (compression set ∼25–30%) seems to be sufficient.

The performance of bell and spigot joints of PVC with respect to the burial depth, the bedding conditions and the loading position has also been studied (García & Moore, 2013). The results revealed that several issues may arise (vertical deformations, changes in pipe diameter, rotation and shear forces) but the leak tightness of the joints under

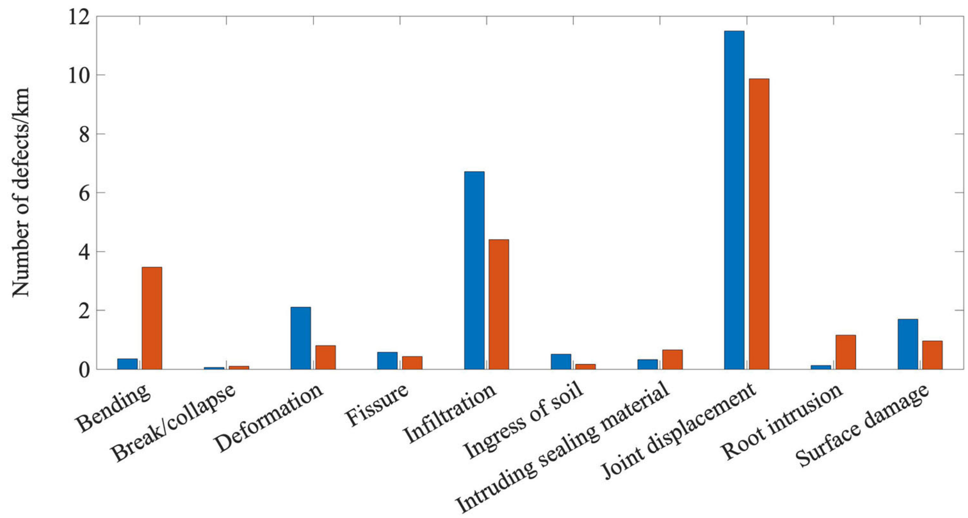

Figure 4. The number of defects per kilometre observed in CCTV inspections for PVC sewer pipes in two Dutch municipalities: Almere (blue) and Breda (red).

the imposed conditions was not assessed. Balkaya and Moore (2009) investigated the interaction between a Rieber-type PVC gasket and the pipe with the means of finite elements modelling (FEM). The results from the analyses revealed that the friction coefficient affects the stiffness of the joint and that increased gasket modulus leads to increased insertion force and bending moment. In a later publication (Balkaya, Moore, & Sağlamer, 2012), the same model was studied in order to test the bell and spigot-jointed PVC water pipes that lie on non-uniform bedding, which was simulated by voids of different sizes. The conclusions derived by FEM included higher deformations in the case of improper bedding under the joint and lower deformations in the case of stiffer soils around the pipes.

PVC pipes in practice

Inspection (CCTV) data from two Dutch municipalities (Almere and Breda) indicates that plastic pipes are used extensively (∼50% of each system) for urban drainage purposes. Polyvinyl chloride is the most popular material especially for gravity sewers (49% in Almere and 36% in Breda). In Almere, the youngest city in the Netherlands largely built after 1970, the existence of two different sub-systems is profound: a storm sewer system constructed mainly of concrete pipes and a dry waste water sewer system constructed mainly of PVC. In Breda, there is a variation of installed plastic pipes in terms of construction materials and types of application (storm water, wastewater and combined system).

The examination of the available inspection data sets reveals the presence of a range of defects, affecting the structural stability, flow regime and leak tightness of the system. Figure 4 presents the occurrence rate of such defects in PVC pipes (number of defects normalised per kilometre), classified according to NEN 3399 (2015). In this study, the defects are grouped without considering the level of severity in order to compensate for the uncertainty involved in CCTV inspections (Dirksen et al., 2013).

Detailed exploration of the available data sets proved that there is not a clear pattern that could link the use of a PVC pipe, a specific range of diameters or other characteristics of the system to increased levels or exclusive types of defects. This fact might be attributed to the limited available data (506 km of PVC pipes in Almere and 206 km in Breda), especially since there is a minimal variation in the data set of Almere.

Another approach was implemented for the PVC pipes (2.4 km) in the municipality of Amstelveen. In an effort to verify whether the degradation of PVC systems is depicted, inspection data of pipes that have been inspected twice was explored. This analysis (Figure 5) reveals an increase in the occurrence rate of the initially found defects, followed by the appearance of new ones (breaks, fissures and root intrusion). These changes are noticed within a timespan of 7–8 years.

Critical aspects

Evaluation of the literature

Inspection data indicates that PVC is the most used construction material for sewer systems. Although some researchers focused on operating PVC pipes in sewers, research was restricted to measuring only deflection levels (Moser et al., 1990; Walton & Elzink, 1989) or conducting visual-based assessments (Meerman, 2008). Bauer (1990) made a more comprehensive assessment of an operating pipe, but testing included merely one pipe which had served for 15 years only. Additionally, despite some visual assessments of the joints used in sewer pipes (Bauer, 1990; Meerman, 2008), there is hardly any relevant research reported on the effect of the sewer environment on the elastomeric material properties and performance. There are indications, however, that the hostile environment that prevails in sewer systems (acids, FOG, etc.) has an impact on certain sealing materials, such as natural rubber and styrene–butadiene rubber (Plastics Industry Pipe Association [PIPA], 2009). Moreover, addition of certain mixture components and softeners in the production of sealing rings could trigger a type of material incompatibility with PVC pipes, resulting eventually in corrosion and leakages (Stein, 2001).

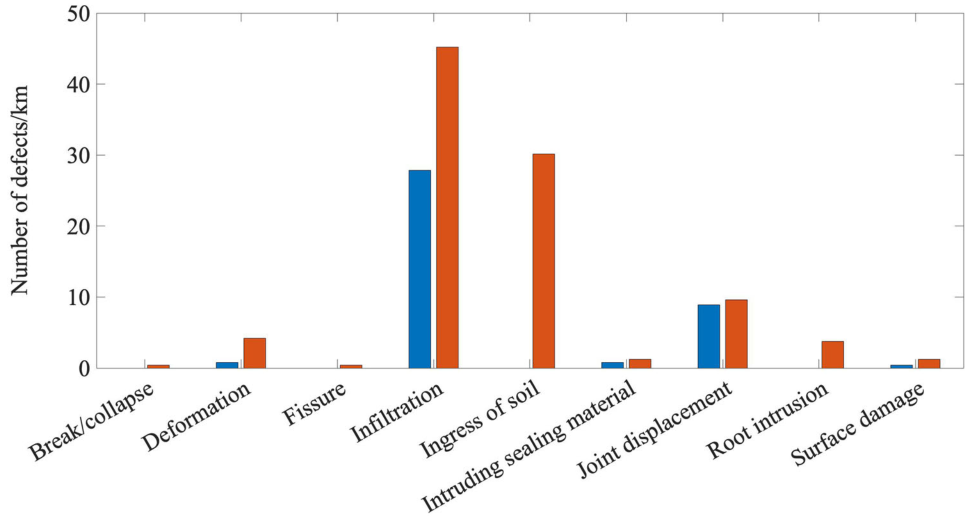

Figure 5. The number of defects per kilometre observed in CCTV inspections of the same PVC sewer pipes in the municipality of Amstelveen in 2003 (blue) and in 2010/2011 (red).

The need for comprehensive testing is implied by this literature review. For instance, while a connection between extrusion quality and tensile properties could be partially established in one study (Alferink et al., 1995), this was unfeasible in another case (Whittle & Tennakoon, 2005). In fact, in the latter study a physical property (i.e. specific gravity) was utilised to explain the differences in the mechanical (tensile) properties.

Comparing and combining results from different researchers in order to draw conclusions is challenging, due to a.o. a lack of uniformity in materials and methods applied. The conditions and methods of specimen preparation and testing are based on different standardised (ISO, ASTM, AS/NZ) or non-standardised methods. Additionally, the production quality of new pipes used as reference specimens has changed over the years, making the direct comparison with aged pipes just indicative. Finally, comparing individual properties with respect to the requirements of norms for safe operation of PVC sewer pipes does not provide any indication concerning material degradation, as the exact initial conditions are still unknown.

A property that is used extensively in design and classification of gravity sewer pipes is pipe stiffness. Research (Välimaa, 1982) has proved that under high soil covers (as for sewer pipes), pipe stiffness is not the most crucial parameter. However, it is expected to become significant for house connections which are usually placed under soil covers <0.8 m. Besides that, in the explored literature a confusion between ring (or nominal) stiffness and pipe stiffness has been noticed. The respective formulas as included in ISO 9969 (2016) (Equation (9)) and ASTM D 2412 (Equation (10)) are provided for clarification:

$$S = \left(0.0186 + 0.025 \cdot \frac{y}{d}\right) \frac{F}{L \cdot y} \tag{9}$$

where S $(or\ SN)$ is the ring stiffness, y is the deflection (m), d is the average inside diameter, F is the applied force (kN) and L is the length of the test piece (m).

$$PS = \frac{F}{\Delta_y} \tag{10}$$

where PS is the pipe stiffness, F is the applied force (N/m) and Δ_y is the deflection (m).

In terms of elastic modulus, ring and pipe stiffness are expressed as (Moser & Folkman, 2008):

$$SN = \frac{E \cdot I}{D^3} \tag{11}$$

$$PS = \frac{6.7 \cdot E \cdot I}{r^3} = 53.7 \cdot \frac{E \cdot I}{D^3} \tag{12}$$

where E is the modulus of elasticity (Pa), I is the moment of inertia of pipe wall per unit length (m^4/m) and D is the mean diameter (m). An additional remark concerning pipe stiffness is on its attributed unit. Using kPa or psi for this property has no physical meaning and confusion among engineers may be caused. As indicated in Equations (9) and (10), pipe stiffness is a measure of the resistance of a pipe expressed as a ratio between the applied linear loading in the longitudinal direction (kN/m) and the vertical deflection in the radial direction (m). Therefore, the unit should be strictly notated as $kN/m_{linear}/m_{deflection}$ or $lbf/in_{linear}/in_{deflection}$ instead of kPa (=kN/m^2=loading/area) or psi ($lbf/in.^2$) respectively.

Inconsistency between scientific literature and practice

A recent study (Kuliczkowska & Zwierzchowska, 2016) presented a range of early defects found on newly installed PVC sewer pipes during CCTV inspections. These defects included dents due to installation or soil compaction, excessive deflections, buckling and improper longitudinal slopes. Inspection data from Breda and Almere indicates that additional defects may emerge: surface damage, fissure, displaced/destroyed sealing ring, root intrusion and break/collapse. Given the limitations that exist in CCTV inspections due to subjectivity of the inspector and only inner pipe inspection (Dirksen et al., 2013; Van Riel, 2017), defects not reported may also occur as CCTV inspections likely result in an optimistic estimate of the pipe's condition.

Although linking the observed defects in CCTV to the actual physical state of a pipe is arduous (Van Riel, 2017), it is quite apparent that there is a certain gap between scientific research and what is observed in practice. Relevant studies (Folkman, 2014; Meerman, 2008; Whittle & Tennakoon, 2005) suggest that PVC sewer pipes are expected to exceed a 100 years of lifetime, whereas inspection data suggests that severe defects (cracks and fissures) already exist.

The most emphasised discrepancy is observed regarding the performance of elastomeric joints. The literature (Arsénio, 2013; Meijering et al., 2004) indicates that leakage is possible only under extreme cases (deflection, >36%; bending angle, >10° and complete pull-out) and root intrusion is impossible, given that installation is proper (Sadler et al., 2001). However, this comes in contrast to the presented failure rates (Figures 4 and 5), as well as the results of CCTV inspections published concerning Sweden (Östberg, Martinsson, Stål, & Fransson, 2012; Ridgers, Rolf, & Stål, 2006; Stål, 1998) and Denmark (Randrup, 2000). Applied installation techniques (proper laying and jointing) could be considered as an indisputable contributing factor (Stein, 2001; Stephens & Gill, 1982); however, it is unknown whether or not it is the only or most significant one.

Conclusions

Production, installation and operation include numerous factors which can affect the lifetime of a PVC pipe. These factors appear to interact with each other under certain conditions resulting in different failure mechanisms. Four lifetime prediction models (i.e. SEM, Arrhenius equation, LEFM and quality number) have been utilised in the literature in order to describe some of these failure mechanisms and conclude on the residual lifetime of plastic pipes. However, given their limitations, the predicted lifetimes are certainly open to dispute, as no model encompassing all possible failure mechanisms has been proposed yet.

Research on material degradation reveals that the properties of PVC sewer pipes in operation have not altered significantly or at all, whereas a lifetime that exceeds 100 years is usually suggested. Only one case of failure is recorded, concerning a sewer main, and the failure was attributed to poor extrusion quality. However, there is no published research on the effect of sewage on the elastomeric seals of PVC systems.

Inspection data from three Dutch municipalities highlights that PVC sewer pipes have already developed all types of known defects, whereas degradation evolves with time at a relatively fast rate. Analysis of a larger inspection data set will allow the detection of a possible connection between defects (types, rates) and elements of the system (diameter, type of drainage pipe, soil cover, etc.).

There is a certain discrepancy between literature and observations in practice on the issue of lifetime expectancy of PVC sewer pipes. This emphasises the need for further material properties assessment of operating PVC sewer pipes and elastomeric joints. Additionally, only comprehensive testing of physical, mechanical and chemical properties could yield safe conclusions regarding the level of degradation and its origins. In the literature, efforts to determine just individual properties have proved to be inadequate, leading to inconsistencies and unanswered questions.

List of symbols

A	Constant in Equation (5) (-)
a	Crack length (m)
a	Reduction in pipe perimetry (m)
a_f	Crack size at failure (m)
a_o	Initial flaw size (m)
B	Constant in Equation (4) (-)
C	Constant in Equation (3) (-)
D	Mean pipe diameter (m)
D_m	Mean pipe diameter (m)
d	Mean inside diameter (m)
d	Pipe wall thickness (m)
E	Creep/relaxation modulus (Pa)
E	Modulus of Elasticity (Pa)
E_a	Activation energy of reaction ($J \cdot mol^{-1}$)
F	Applied load on a tested pipe length (N)
F	Applied load per length of tested pipe ($N \cdot m^{-1}$)
I	Moment of inertia of pipe wall per unit length ($m^4 \cdot m^{-1}$)
K_I	Stress intensity factor in mode I type of loading ($Pa \cdot m^{0.5}$)
k	Degradation reaction rate constant (s^{-1})
k_e	Extrapolation factor in ISO 9080 (-)
L	Length of tested pipe for measuring ring stiffness (m)
l_o	Overlap length (m)
M	Measured values of a piping system's property (-)
m	Constant in Equation (5) (-)
n	Constant in Equation (4) (-)
PS	Pipe stiffness ($N \cdot m^{-1} \cdot m^{-1}$)
Q	Quality number (-)
R	Gas constant ($J \cdot K^{-1} \cdot mol^{-1}$)
R	Mean radius of pipe (m)
R	Reference value of a piping system's property (-)
S	Ring stiffness ($N \cdot m^{-1} \cdot m^{-1}$)
s	Pipe wall thickness (m)
SN	Ring stiffness ($N \cdot m^{-1} \cdot m^{-1}$)
T	Temperature (K)
t_{in}	Time of crack initiation (s)
t_{SCG}	Slow crack propagation time (s)
W	Weighting factor of a piping system's property (-)
y	Vertical deflection of pipe (m)
Δ_y	Vertical deflection of pipe (m)
σ	Compressive/tensile residual stress (Pa)

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No potential conflict of interest was reported by the authors.

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Appendix

Table A1. Measured deflection levels of PVC sewer pipes.

Area	DN/SDR	Soil	Surround material	Age (years)	Deflection (%)		Reference
					Mean	Maximum	
Dartford (England)	457/41	Chalk	Pea gravel	2	1	3	Walton and Elzink (1989)
				17	1	3	
	406/41	Chalk	Pea gravel	2	1	2	
				17	1	2	
	273/41	Chalk	Silty sand	2	2	4	
				17	2	5	
Dragör (Denmark)	400/34	Sand with fine clay part	Sand	0.5	2	5	
				13	3	5	
	400/41	Sand with fine clay part	Sand	0.5	2	7	
				13	4	7	
Lelystad (The Netherlands)	250/41	Fat clay	Sand	2	3	5	
				14	3	5	
	250/41	Fat clay	Sand	2	3	6	
				14	3	6	
Buckie (Scotland)	244/44	Loam with gravel	Coarse sand	6	3	5	
				20	3	5	
	244/44	Loam with gravel	Coarse sand	6	3	7	
				20	3	7	
	244/44	Loam with gravel	Coarse sand	6	4	9	
				20	4	10	
	323/44	Loam with gravel	Coarse sand	6	3	7	
				20	3	7	
	244/44	Loam with gravel	Coarse sand	6	7	13	
				20	7	14	
USA	254/NA	Gravel pit	Silty fine sand	0.01	3.6	–	Moser et al. (1990)
				0.1	4	–	
				1.1	6	–	
				11.4	6.1	–	
	254/NA	Gravel pit	Silty fine sand	0.01	3.2	–	
				0.1	3.5	–	
				1.1	5.5	–	
				11.4	5.6	–	
	254/NA	Gravel pit	Silty fine sand	0.01	2.8	–	
				0.1	3.3	–	
				1.1	5.2	–	
				11.4	5.2	–	
	254/NA	Gravel pit	Silty fine sand	0.01	2.1	–	
				0.1	2.9	–	
				1.1	4.2	–	
				11.4	4.3	–	
Kauniainen (Finland)	315/34	Silt-Siltmoraine	Gravel	0.01	–	1.1	Välimaa (1982)
				9.5	–	2.7	
	315/34	Silt-Siltmoraine	Gravel	0.01	–	1	
				9.5	–	3.2	
	315/51	Siltmoraine	Sand	0.01	–	2	
				9.5	–	2.9	
	315/51	Siltmoraine	Siltmoraine	0.01	–	3.3	
				9.5	–	4.2	
	315/51	Rock	Sandy silt	0.01	–	1.4	
				9.5	–	6.2	
Gerzat (France)	200/51	Sand		25	2.5	–	Alferink et al. (1995)
Montpellier (France)	315/51	Rock		23	7.5	20.5	
St. Agathe (France)	400/41	Sand		25	5.5	11.5	
Courchevel (France)	315/41	Sand		12	7.5	20	
Odense (Denmark)	160/41	Sand		23	13	17.5	
Nykobing (Denmark)	200/34	Sand		30	2.5	6	
	200/41	Sand		28	4	7	
Notteroy (Norway)	250/51	Clay		22	10	16	
Torshalla (Sweden)	200/41	Sand		24	8	12.5	