100 years lifetime of plastic pipes

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Commissioned by the European Plastic Pipes and Fittings Association

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Executive summary - 100 years lifetime of plastic pipes

The lifetime of plastic pipes has been often discussed in the last few decades. Generally, the design point specified by standards in pressure applications is set at 50 years. Contrary to that, there has been no reference regarding the design life in international product standards for non-pressure pipe applications. However, it is well known that the product standards for plastic pipes are conservative compared to the real operating conditions to avoid premature failures in both pressure and non-pressure applications. Therefore, the safe service life may very well exceed the design life of 50 years. Often discussed is the possible safe use of plastic pipes up to 100 years. The presented meta-study, commissioned by The European Plastic Pipes and Fittings Association, aims to summarize the available literature on plastic pipes' lifetime with a focus on the possibility of confirming the expected 100 years service life.

The study covers pressure and non-pressure polyethylene, polypropylene, and unplasticized polyvinyl chloride pipes, including both smooth and structured-wall pipes for the transportation of potable water, natural gas, sewage and drainage waters. In addition, the analysis accounts for operational temperatures around the pipes of maximum 20°C, and under the assumption of adherence to contemporary standards (EN, ISO and ASTM, mainly) throughout the production, trenching, and operational phases. Notably, this study excludes investigation into industrial pipe systems employed for conveying aggressive media and pipes designated for floor heating applications, or the use of non-virgin materials.

The meta-study is based on references, including scientific publications in peer-reviewed journals, protocols, reports, standards, and conference presentations. Most of these are based on dig-out studies of pipes operating for up to 50 years. A clear statement of 100 years and more was found in 23 references (13 for pressure applications, 10 for non-pressure applications). These statements were given by different research groups and individuals, using different experimental evaluation approaches.

The main lifetime estimation method for pressure pipes is the hydrostatic pressure test performed at different temperatures in combination with Arrhenius type extrapolations to application temperatures. Additionally, the fracture mechanical description of a propagating crack, in combination with the experimental determination of crack growth rate, allows conservative estimation of lifetime. For non-pressure pipes, it is mainly the stress relaxation tests at a constant pipe deflection, that can be used to determine pipe’s performance. Another method is the Rate Process Method, which is based on junction stress tests to failure at various load and temperature conditions for corrugated pipes. These are used to predict failures caused by stress cracking. For material degradation of certain additives, the most commonly used procedure is based on the measurement of oxidative induction time for both pressure and non-pressure applications.

Reports on failures of either pressure or non-pressure plastic pipes were hardly found in literature. Cases of failed pipes that were found were caused by not following the standardized process of manufacturing, which resulted from the presence of foreign inclusions, or improper installations - mainly faulty trench backfill and poor joining. It is worth pointing out that no failure was found to be caused by material aging or incorrect pipeline design.

Based on the results of all examined studies and our judgment of the procedures used in those studies, the following can be concluded. As long as all steps in the process of design, manufacturing, trenching, and operating conditions follow currently valid EN and ISO standards for pipes, fittings and valves and installation of the plastic pipe systems, the actual lifetime of the pipes can be expected to be well above 100 years.

Table of contents

1 Introduction

Plastic pipes have been used since the late 1930s for both pressure and non-pressure applications. The first ever used pipes were made of polyvinyl chloride (PVC) for drinking water distribution and gravity drainage systems in various residential areas in Germany. Subsequently, in the late 1950s, polyethylene (PE) pipes gained popularity, followed by polypropylene (PP) pipes in the 1980s, diversifying the options available for different applications.

Despite the original design life of 50 years, some of the first-used PVC pressure pipes continue to transport water under 4-5 bar efficiently up to date. In an analysis carried out by Nowack et al. [1] after 50 years of operation, these pipes showed outstanding results. Based on the hydrostatic pressure tests at an elevated temperature of 60°C, it was concluded that even if the internal pressure was doubled to 8-10 bar, the lifetime expectancy would be another 50 years, making the total lifetime more than 100 years. This raises questions such as 'What is the actual lifetime of plastic pipes?' or 'How long can they be safely used in service?'.

To answer these questions, this meta-study on available information regarding the possible lifetime of plastic pipes was commissioned by the European Plastic Pipes and Fittings Association. The basis of this meta-study is available literature, such as reports and scientific publications, conference presentations, dig-out studies, current standards and available extrapolation methods used in industry and/or research.

The focus of this study is limited to thermoplastic pipes made from PE, PP and PVC-U used in pressure or non-pressure applications for the transportation of potable water, natural gas, sewage and drainage waters. Furthermore, operating temperatures of the pipes are considered to be up to max. 20°C and that the pipes were produced, trenched and operated according to currently valid standards, such as EN, ISO or ASTM. Industrial pipe systems used for transportation of aggressive media, as well as pipes used for the transportation of heated media (e.g. floor heating) are not part of this study.

The study consists of a short introduction to design, service, as well as overall lifetime of polymer pipes and two chapters focusing individually on the available literature for pressure and non-pressure pipes.

2 Definition of lifetime

2.1 Design life vs. service life vs. lifetime

The design life of a plastic pipe must be distinguished from the service life or the expected lifetime. The meaning of these terms is defined as:

- Design life: The design life of a plastic pipe is the time during which it is expected to function by its producer, as long as the application conditions meet the specified boundary conditions.
- Service life: The service life is the time defined by maintenance operators. The end of service life can be either a failure or an operator's decision. Based on these two possibilities, the actual service life can be both longer, or shorter than the design life, as shown in Figure 1 below.
- Lifetime: The actual lifetime is the time for which a pipe operates until the pipe's failure. This time can vary significantly based on the actual boundary conditions of, e.g. the installation and operational conditions. For example, in the case that a pipe is operated at lower pressure, or temperature than specified in standards, the intrinsic lifetime of the pipe before failure can be much longer than the design life. If the lifetime is known to be longer than the design life, it would also be possible for operators to safely increase the service life, thus improving the overall performance of plastic pipes.

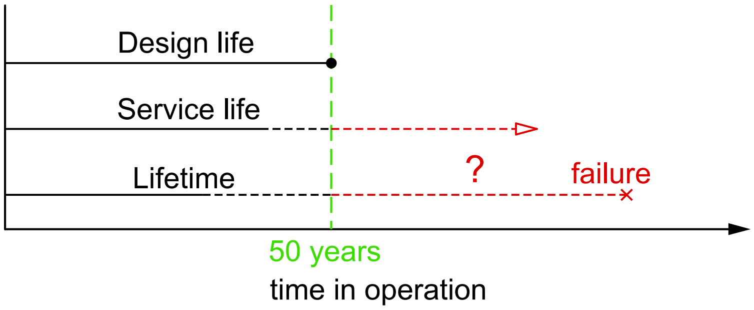

Figure 1: Graphical representation of the terms of design time, service time and lifetime.

2.2 Beneficial factors for the expected lifetimes of pipes

Generally, the maximum design life for a plastic pipe is always stated as 50 years. However, if the manufacturing and operating conditions are in accordance with standards, the lifetime of a plastic pipe is expected to exceed the design life of 50 years due to several beneficial reasons [2; 3; 4]:

- Lower ground temperature than 20°C in 1 m depth underground
    - In the UK (Halesowen, West Midlands), between 6 and 15°C [5]
    - In the Czech Republic (Northern Moravia region), between 0.5 and 17°C [6]
    - In Germany (Potsdam), between 2 and 19°C [7]

Seeing that failures in polymeric materials are usually temperature dependent, a lower temperature in the case of static loading usually leads to slower failure initiation and propagation. Therefore, a lower ground temperature can be seen as a beneficial factor.

- Lower temperature of sewage water in operation compared to standards (for non-pressure pipes)
    - According to measurements performed in different places in Austria and Germany, the average temperature of sewage water during the day measured outside of buildings was 25°C, with the maximum staying below 30°C [8]. The design standard considers 45°C (for diameter ≤ DN 200) or 35°C (for diameter > DN 200)) [9].

Similar to the ground temperatures, the temperature of the transported media also affects failure mechanisms. Thus, a lower temperature of transported media can also be seen as beneficial with regard to achievable lifetimes.

- Tolerances for wall thicknesses are always 0+ tolerance range
    - PE [10; 11]
    - PVC-U [12]
    - PP [13]

According to standards, pipe walls always have to be at least as thick as the given number. In reality, this means that pipe walls are produced thicker than required to ensure meeting this minimum requirement. Seeing that a thicker pipe wall leads to lower stresses and strains under the same loading conditions, this also reduces the driving force of damage mechanisms, compared to the minima required in the standards.

- Design coefficient used in the design [14]

As is typical in all engineering applications, design coefficient is included in the designs, to ensure meeting the design life safely.

- Lower internal stress level in pipes in operating conditions than in the design (for pressure pipes only)
    - $p_{\text{int, max}}$ = 7 bar in the Czech Republic for water [15]
    - $p_{\text{int, max}}$ = 0.05 bar in the Czech Republic for gas (in low-pressure systems) [16]
    - $p_{\text{int, max}}$ = 0.1 bar in the Netherlands for gas [17].

In the case of pressurised plastic pipes, the actual internal pressure is usually significantly below the maximum operating pressure (MOP) on which the standards are based. This of course also reduces the stresses in the pipe, which in turn can lead to longer lifetimes compared to the design life of 50 years.

3 Pressure pipes

3.1 Design life

The 50 year design basis and minimum expected lifetime for pressure water or gas pipe systems is secured by the hydrostatic pressure tests carried out at different temperatures defined by ISO 1167-1 [18] and ISO 1167-2 [19] with the following extrapolation of the results in accordance with ISO 9080 [20]. The extrapolation method defined in ISO 9080 provides an estimation of the 97.5% lower prediction limit of the stress (σ_{LPL}), which a thermoplastic pipe is able to withstand for 50 years at 20°C. The estimated σ_{LPL} is then used to determine the minimum required strength (MRS) for thermoplastic pipe material in accordance with ISO 12162 [14], where a classification and designation system is established. For example, PE materials with $\sigma_{\mathrm{LPL}} = 9$ MPa falls to a range of $8 < \sigma_{\mathrm{LPL}} < 10$ MPa. Thus, the MRS of this material equals 8, and the classification number equals 80. The material designation is then PE80.

Additionally, ISO 12162 allows the determination of categorized required strength $\mathrm{CRS}_{\vartheta,\,t}$, which is used for design purposes at times other than $t = 50$ years and constant temperatures other than $\vartheta = 20°\mathrm{C}$. Note that $\mathrm{CRS}_{20,\,50} = \mathrm{MRS}$.

ISO 12162 also specifies a method for calculating the design stress σ_{S} from the MRS and a design coefficient C ($\sigma_{\mathrm{S}} = \mathrm{MRS/C}$) or $\sigma_{\mathrm{S},\,\vartheta,\,t}$ calculated from $\mathrm{CRS}_{\vartheta,\,t}$ and a design coefficient C ($\sigma_{\mathrm{S},\,\vartheta,\,t} = \mathrm{CRS}_{\vartheta,\,t}/\mathrm{C}$). Unless otherwise specified in a specific product standard, a minimum design coefficient for PE80 and PE100 is for water ($\mathrm{C}_{\mathrm{min}} = 1.25$) and gas ($\mathrm{C}_{\mathrm{min}} = 2$) [11]. Coefficients of other materials are also specified.

Even though the design life is 50 years, in several standards (e.g. [21; 22; 23]) it is already noted that "Research on long-term performance prediction of existing PVC and PE water and gas distribution systems shows a possible service life of at least 100 years".

3.2 Service life expectations based on the available dig-out studies

A number of experimental studies have been conducted on exhumed PE and PVC pipes to examine the premise that material degradation is neither occurring nor affecting mechanical properties and, thus, the potential service life. The main results are described below, separately for both materials. In the case of pressure pipes, no studies were found on polypropylene pipes.

3.2.1 Polyvinylchloride (PVC)

In 1981 [24], Kirby investigated failures in PVC pipes in England that had transported water for over 15 years (laid in the 1960s). It was noticed that the early PVC installations suffered from high failure rates – higher than cast iron pipes. Most of these failures (above 50%) were related to improper installations, mainly faulty backfill and poor joining. These problems were removed in time, and since 1973, the failure rate of PVC pipes has dropped below cast iron pipes.

In 1985 [25] Lancashire investigated five PVC-U pipes with a diameter of 102 mm that were transporting water under up to 5.5 bar for 4 to 16 years. The experiments performed were DSC measurements, tensile tests, C-ring tests, and hydrostatic pressure tests. The tensile properties were found unaffected by the pipes' age. The level of gelation was studied by DSC – it varied between 49 and 64%. In all the exhumed pipes, particles in sizes up to 0.5 mm were detected by X-radiography. From the fracture surface analysis, inhomogeneous regions up to 1.3 mm were apparent. Combining large inhomogeneous regions with a low gelation level would make the pipe perform poorly. However, based on the hydrostatic pressure test, the expected lifetime would still exceed 50 years. The main conclusion was that the decisive parameter in terms of lifetime is the pipe's quality coming from the manufacturing process, not the time in use.

In 1995 [1] Nowack et al. and later in 2005, Hülsmann and Nowack [26] published works on PVC pipes from the early production years of the late 1930s that transported water under 4-5 bar for 23 and 50 years. Long-term hydrostatic pressure tests were performed at the elevated temperature of 60°C. Based on the results, the authors concluded that even if the operating pressure was doubled to 8-10 bar, the lifetime of these pipes would overreach 100 years, including the safety factor C = 1.5.

In 1996 Alferink et al. [27] tested exhumed PVC pipes with up to 37 years of use for water transportation (installed between 1955 and 1980). Based on the results, it was concluded that strainability, ductility, and resistance to internal pressure had been virtually unaffected by aging and were still at the same level as new pipes. It was also shown that there had been progress in the processing of the PVC as most of the older pipes showed much lower gelation levels compared to the newer pipes (51% - 56% vs. more than 80%). Above all, it can be expected that PVC pipes produced according to standard requirements will maintain their functional properties for more than 50 years.

In 2001 [28] (later in 2012, reprinted as PIPA report [29]), Stahmer and Whittle analyzed PVC pipes in diameters from 20 mm to 200 mm transporting water for 30 years in North Western Victoria (Australia). The reported peak ground temperatures, at a depth of 500 mm below the surface, ranged from 13°C in August to 27°C in February. Therefore, the pipes were installed with a minimum of 750 mm of cover, increasing to 900 mm at road and rail crossings, with no special provision needed to be made for elevated-temperature operating conditions. Based on the experimental results of resistance to flattening, gelation, and tensile and fracture toughness measurements, it was concluded that there had been no degradation in the strength or elongation characteristics of the PVC during the service life of the pipes. Even though the degree of gelation was expected to be higher than the 44-60% measured by DSC, the exhumed pipes had not suffered any loss of strength as a consequence of operating under pressure.

In 2005 [30] and 2006 [31], Breen studied five excavated PVC pipes that were manufactured between 1959 and 1997, and were transporting water for 6 to 42 years. Measurements were performed to quantify the residual effective stabilizers concentration, the distribution of stabilizers, the composition, the molecular weight distribution, and the degree of gelation. Furthermore, craze initiation and slow crack growth experiments, fatigue, impact measurements at low temperatures, and burst tests were performed on excavated PVC pipes. From the point of view of chemical degradation, it was calculated that the induction period for the dehydrochlorination process for the excavated pipes at 15°C would be thousands of years. Thus, chemical degradation does not limit the lifetime of studied pipes for the next 100 years. Based on the mechanical testing results, it was concluded that the expected lifetime exceeds 100 years under the conditions that the stress in the PVC pipe wall does not exceed 12.5 MPa and no crack initiation or other mechanical damages have occurred in the pipes yet. The exceptions were stated for pipes made during the 1970s, as they suffered from a lower degree of gelation (below 40%). However, those pipes can still operate for at least 100 years under conditions that will not cause stress raising (low water pressure, insignificant water pressure fluctuations, no digging activities, no new connection installations).

In 2008 [17], Hermkens summarized the results of tests on PVC-U pipes transporting gas under up to 0.1 bar for up to 50 years in the Netherlands. Impact tests showed no significant decrease in impact resistance with respect to time in service. The impact resistance of the PVC-U pipes, which have been in use for up to 50 years, has been mainly dependent on the initial quality fixed during the production of the pipe. Despite reaching the design life of 50 years, PVC-U seems to be as good as it was years ago, based on the limited number of test results.

In 2014 and 2015 [32; 33; 34], Folkman released several works where he described and commented on experimental measurements performed in [35] on excavated PVC pipes that had been transporting water for up to 49 years. The pipes were installed between 1964 and 1994. The performed experiments included pipe dimensions measurements, acetone immersion, and pressure tests. Out of these 8 studied pipes, two failed the acetone test, and one of these two failed even the pressure test. These failures were explained by the gelation problem that was addressed at the time the pipes were made – in the 1970s and 1980s. Based on the experimental results, it was concluded that the ability of the 49 year old pipe to perform its intended purpose had not changed. The pipe had the same water pressure capacity it had when it was installed 49 years ago.

<u>Prediction models only:</u>

In 2021, Laarhoven et al. [36] presented results from a lifetime prediction stress-based model Comsima for PVC-U pipes. Three scenarios with the real input parameters from a study on excavated pipes [30], including their uncertainties up to 10%, were analyzed. Based on the obtained results, it was stated that the size of the initial imperfection is the most influential parameter as it causes a difference in lifetime of decades. Thus, when the size of the imperfection in these scenarios was adjusted to 0.85 mm, which corresponds to the 90th percentile of the assumed distribution of particle sizes, it turns out that only a high water pressure or high residual stress can lead to failure before 100 years. On the time scale relevant to the drinking water context (~100 years), the model is very sensitive to variations in parameter values. A few percent uncertainty in one of the different parameters leads to uncertainty in the moment of failure of decades. It is, therefore, unlikely that this model can be used effectively to correctly predict a failure moment based on measured data. However, the model may be used for retrospective analysis of failures on important mains. In that case, information on model parameters can be collected with sufficient accuracy.

3.2.2 Polyethylene (PE)

In 2001 [4], Schulte showed experimental results of hydrostatic pressure tests and creep tests of two types of HDPE - Hostalen GM 5010 T3 black (PE80 class) and Hostalen CRP 100 (PE100 class). Based on these results, it was concluded that the high-quality plastic pipe materials available on the market have a reliable service life of more than 100 years. Reasons were given for very conservative conditions in pipeline design compared to actual operating conditions - much higher internal pressure, use of safety coefficients in the design, and lower environmental influence (pipes are usually buried and therefore better protected).

In 2003 [37], the U.K. Water Industry published guidance on the choice of pressure classifications or ratings for buried and above ground polyethylene pipe systems. Based on the hydrostatic pressure tests of MDPE PE80 pipes that were run at different temperatures of 20, 60, and 80°C, it was concluded that extrapolation beyond 140 years according to ISO 9080 should be permitted.

In 2006, Schulte and Hessel [38] investigated HDPE (Hostalen GM5010) pipes (SDR = 11) that were installed in 1961 in Frankfurt and were transporting water until 2002. The operating conditions were: internal pressure 4.5 bar and a temperature of 20°C. No evidence of thermal aging was found in the studied pipes. Hydrostatic pressure tests were performed at different temperatures. Based on the obtained results, a remaining service life of 124 years was predicted at an operating pressure of 4.5 bar (without considering thermal aging). The thermal aging process was then described by the Arrhenius equation. It was estimated that thermal aging would not occur for at least another 27 years, reaching a total lifetime of the pipes of at least 68 years.

In 2007, Hessel [39] estimated that the time until all thermal stabilizers in PE100 material are consumed based on thermal aging measurements performed at higher temperatures is more than 460 years. Therefore, the minimum lifetime for PE100 pipes can safely exceed 100 years at 20°C.

In 2008, Hoang and Lowe [40; 41] published work that examined the loss of antioxidants in PE100 water pipes over a decade of exposure to water in hydrostatic pressure tests at temperatures from 20 to 80°C. The depletion of antioxidants due to leachate by water and consumption reaction to protect the pipe against thermal oxidation was monitored by the oxidative induction time (OIT) testing. The presented models based on Arrhenius law were used to predict the lifetime of the studied pipes. The extrapolated time to total depletion of antioxidants proved to be longer than 50 years – for the internal pipe surface, 69 years for 20°C and 194 years for 10°C. It is worth noting that the approach used in this work simulated the worst-case scenario – both internal and external environments in hydrostatic pressure tests were water, while, during service, only the internal surface of the pipes is exposed to water. Furthermore, the test water was de-ionized. The practical experience proved that de-ionized water accelerates the degradation of the pipe compared to non-de-ionized water. Therefore, it is expected that the service lifetime of this PE100 pipe material is greater than the lifetime determined in this work.

In 2009, Frank et al. [42; 43] investigated four different PE pipes that were transporting gas and water for up to 30 years. The molecular analysis did not show any significant polymer degradation as an indication of the aging of the materials. Moreover, the thermomechanical behaviour delivered comparable values to the reference materials. The absence of post-crystallization on the outer pipe wall and a still existing typical amount of residual stresses showed that the mechanical material properties had been almost unaffected. Distinct OIT values and clearly detectable amounts of stabilizers in the pipes ensured sufficient stability for a continuation of service. Fracture mechanics investigations showed a decrease in failure times with pipe age. Extrapolating creep crack growth through fatigue tests predicted sufficient stability for both pipes to remain in good order for 50 years despite not considering crack initiation times in the estimations.

In the PIPA report from 2010 on the life expectancy of plastic pipes [44], it was pointed out that based on the use of 50-year stress regression data, it has been incorrectly assumed that plastic pipe systems have a life expectancy of 50 years. The reason for this statement is that the lifetime is dependent on many factors (manufacture, transport, handling, installation, operation, protection from third-party damage, and other external factors). Provided that PE pipeline system components are appraised and supplied to nominated industry standards under third-party product certification systems, and provided pipelines are designed and constructed correctly, then the likelihood of failure is minimized and, thus, the actual life cannot be predicted but can logically be expected to be well in excess of 100 years before major rehabilitation is required.

In 2019, Schulte et al. [45; 46] analyzed a part of a pipe made of PE63 with SDR = 17, transporting wastewater from 1971 for 47 years on the bottom of Lake Ossiach (Austria). The maximum operating internal pressure was 4 bar, and the maximum temperature of the lake water was 15°C. A pipe was analyzed with respect to slow crack growth resistance, as well as thermal aging properties. With the Arrhenius approach, it was concluded that with respect to both stress crack resistance as well as thermal ageing, the pipe could be operated for at least another 50 years, doubling the design life.

In 2021, Campbell et al. [47] studied the long-term aging performance of PE80 and PE100 pipes, including butt fusions (BF) and electro-fusions (EF) joints, that have been used in the United Kingdom for transporting water for more than 30 years. There has been no evidence of preferential oxidative degradation of joints in this study from Oxidation Induction Time (OIT) testing using a Differential Scanning Calorimeter (DSC) and Fourier Transform Infrared Analysis (FTIR) testing. Physical testing revealed excellent performance of BF joints and mixed performance of EF joints that nonetheless remained intact in the field. Results obtained for all 27 butt fusion welds were acceptable, with a large level of ductility in all cases. Results obtained for EF welds were mixed. Out of a total of 18 EF welds, some with deliberately added flaws, only 7 were found to be acceptable by tests currently available within standards. It was concluded that the projected time to depletion of antioxidants is greater than the assumed minimum design lifetime of 50 years, except for one type of PE80, which was a prototype material. In addition, it is mentioned that this work was able to be used to demonstrate that each of the following properties (tensile, slow crack growth resistance, fracture toughness, Melt Flow Rate

(MFR)) are unaffected in actual service conditions whilst the material has adequate antioxidant protection by measuring each of these properties.

Kuriyama et al. [48] proposed the design concept on the minimum 100 years lifetime of polyethylene piping system for water supply. This concept was successfully verified on pipes made of PE100 with the following design criteria: The maximum allowable water pressure shall be a hydrostatic pressure of 1MPa (20°C). For elevated temperatures up to 40°C, the safety reduction coefficient shall be used. The minimum earth cover should be 0.6m. The allowable radius of curvature shall be equal to or more than 75 times the pipe's external diameter. The pipe shall withstand the damages caused by seismic movement of Level 2 (an allowable strain in the longitudinal direction below 3%). For the 0.1ppm or more residual chlorine existing in the tap water, the pipeline maintains a minimum 100 years of resistance against chlorinated water.

<u>Prediction models only:</u>

In 2015, Mikula et al. [49] predicted a lifetime of welded pipes made of PE100 material using a fracture mechanical description of a propagating crack by finite element simulations in combination with an experimentally determined creep crack growth rate. Among others, the main stated conclusion was that from the perspective of fracture mechanics, it was shown that keeping the weld bead has a positive contribution to the lifetime of welded pipes compared to removing the bead after the welding process is finished. Additionally, in the case of the remaining weld bead, the predicted lifetime of the pipe is comparable with a non-welded pipe. Above all, the estimated lifetimes considering the initial defect of 0.4 mm were around 50 years (without the crack initiation time).

Poduška et al. estimated the lifetime of a PE pipe by methodology based on fracture mechanical description of a propagating crack by finite element simulations and experimental determination of creep crack growth rate. In 2016 [50], the residual hoop stress was investigated in several different pipes made of PE100 materials. It was concluded that the tensile part of residual hoop stress of various PE pipes lies in a range from 0.8 to 1.6 MPa. In 2019 [51], the lifetime of a PE100 pipe was estimated for underground operating conditions with an internal pressure of 10 bar and including residual stress in the pipe wall (considered magnitude was 1 MPa). The initial defect size was considered 0.4 mm. A conservative case of buried conditions was considered – a pipe buried 0.5 m under the surface with heavy traffic loads. Even though the crack initiation time was not taken into account, the estimated lifetimes were well over 100 years.

In 2019 Frank et al. [52] estimated the lifetime of PE pipes made of PE80, PE80-MD, PE100, PE100RC by the same methodology based on fracture mechanical description of a propagating crack and experimental determination of creep crack growth rate. The initial defect size was considered 0.4 mm. It was concluded that the conservative predictions (not including the crack initiation time) of failure times of internal pipe pressure tests at 23°C for four PE pipe grades are of at least 50 years for all materials. Considering additional safety factors (1.25 for water and 2 for gas), pipes made of the studied materials could likely exceed lifetimes of 100 years. However, the impact of Stage III mechanisms must be considered and estimated separately in practical applications.

In 2022, Zha et al. [53] pointed out in their review focused on lifetime predictions of PE pipes that in order to determine the service lifetime under the specific condition, it is necessary to establish a test method that includes the synthesis effect of various important subfactors for application. The studies of current lifetime prediction often consider thermo-oxidative aging only, which is not yet truly suitable for the operating environment. Therefore, it will be a trend to research pipe aging considering more factors. In addition, during the life cycle of PE pipes, whether the ductile or brittle failure occurs in pipes depends on which process is faster for the given surrounding medium, oxygen, external loads, temperature, and defect. Therefore, the lifetime prediction is a trend based on the coupled failure mechanism.

3.3 Conclusions

Research studies on pressurized plastic pipes, particularly PVC and PE, indicate that they are proven to fulfil a design life of 50 years.

In the case of PVC pipes, several failures occurred due to early challenges related to processing and joining. However, with gaining more experience, these problems were solved, and together with the advancements in the manufacturing process of PVC in the 1970s/1980s, the pipes' long term durability has significantly improved. Investigations on PVC pipes that had been in service for 15 to 50 years revealed that properties, such as tensile strength and resistance to stress cracking, remained largely unaffected during application. However, the gelation percentage in most of these pipes was expected to be higher. Overall, it was emphasized that failures during operation are often caused by errors in the pipes' production and installation stages, not by the aging of the material (during the time in use). Thus, if processed and installed correctly, these issues can be mitigated.

Similarly, studies on different PE materials and PE pipes made of PE63, PE80 and PE100 operating for up to 47 years revealed great performance of the pipes. The available research considered stress cracking, as well as material aging. The predicted lifetimes based on both damage mechanisms were far beyond the design life of 50 years, even under the consideration of the impact of potential defects, the presence of residual stresses, or welded joints.

With the PVC and PE plastic pipes on the market today, it can be concluded that correctly installed and operated pipes systems will have a service life exceeding 100 years.

4 Non-pressure pipes

4.1 Design life

Regarding drainage and sewage non-pressure pipes, the design lifetime is not directly specified in the standards for the selected materials of PE [54], PP [55] and PVC [56], as well as for structured wall pipes [57; 58]. The standards define mechanical, physical, chemical, and other properties that the material and pipes should possess and experimental measurements that the material and pipes should pass in order to guarantee safe operation. Examples of such requirements are:

- Hydrostatic pressure test must pass
  - PE: 4 MPa for 165 h at 80°C or 2.8 MPa for 1000 h at 80°C
  - PP: 4.2 MPa for 140 h at 80°C or 2.5 MPa for 1000 h at 95°C
  - PVC: 10 MPa for 1000 h at 60°C
- Thermal stability test (OIT) for PE and PP
  - Must be longer than 8 min at 200°C for PP and longer than 20 min for PE
- The polymer content in material
  - Must be higher than 80% for PVC and 97% for PP
  - Chalk is often used as filler in PVC pipes
- Pipe deflection limits after installation:
  - 8% for PVC, 9% for PE and PP
- Ring-flexibility test up to 30% deflection

The dominant loading that non-pressure pipes are exposed to is caused by the weight of soil and traffic. Contrary to the pressurized pipes, non-pressure buried pipes are thus loaded in a 'constant strain' mode after the soil has settled. In practical terms it means that after the installation and a few years of operation, the soil in the trench settles, which results in a constant pipe deflection and constant strain in the pipe wall. Therefore, the limits of initial and long-term average pipe deflection and acceptable strain are specified in more detail in CEN/TS 15223 standard [59]. The pipe deflection is also dependent on the level of soil compaction. However, it was predicted in a TEPPFA study [8] that the limit of 8% deflection is not reached even after 100 years.

Due to the visco-elastic nature of plastic materials, the induced stress in the pipe wall is the highest at the beginning and decreases (relaxes) with time in use. Therefore, for a short period of time, the stress may be higher than the pipe was tested on, but it quickly decreases under the allowed limit.

In available studies and reports, it is concluded that the lifetime of non-pressure pipes is over 50 or even over 100 years. This is discussed in the next section. Seeing that dig-out studies of non-pressure pipes often deal with combinations of different pipe materials, a clear separation between materials, as in the section for pressure pipes above, is not used in this section.

4.2 Service life expectations based on the available dig-out studies

In 1991 [60] and later in 1995 [61], Janson summarised the results from his previous work on PE and PVC non-pressure pipes in his report. Several different pipe samples were exposed to constant deflection at 23°C for the stress relaxation measurement. The force that was needed to keep the pipe samples deflected was measured for over 5 years. After the first 10 000 h (1.14 years), a prediction of a level of stress presented in the PVC pipe samples after 50 years had been made, based on the calculated compliance (*C*), which has a rectilinear course in the lin *C* vs. log *t* plot after some time. The same prediction was repeated after 5 years of measurements. The comparison of both predictions showed only a slight difference (in some cases, the predicted values were even the same for both). However, in the case of PE samples, the rectilinear part of the compliance curve was reached much quicker – after only 1 000 h, meaning that for the long-term compliance (relaxation modulus) predictions, the measurements need to be performed for much shorter times. It was further observed on these PVC and PE pipe samples, which have been kept constantly deflected, that after release, the E-modulus and pipe ring stiffness values were equal to or larger than the original short-term values. This increase was assumed to be due to the physical aging process taking place in the pipe material.

In addition, it was found that the short-term bending stresses (measured after 3 min.) in the PVC pipe wall will relax to approximately 40 % (30 % for PE) of the original value after 50-100 years of constant bending strain caused by pipe deflection. Based on the predictions of the long-term properties, it was concluded that the service period for standardized gravity thermoplastics sewer pipes can certainly be 100 years or more if properly installed.

In 1995, Alferink et al. [62] studied non-pressure PVC pipes operating at several different locations between 12 and 30 years installed in a poor way. As a result, the measured deformations in these pipes were found to be the upper level of what normally can be expected. The results of the functional tests showed that the pipes still fulfil the stiffness requirements, and their functional and structural integrity is still ensured. It was concluded that considering the fact that raw materials and the pipe production process have been improved since the early years, the study expected that the currently produced PVC pipes fulfilling CEN requirements will last for several hundred years.

In 1996, Janson [63] studied PE and PVC pipes and their materials from several different perspectives: the pipes' mechanical stability, materials' long-term strength, materials' resistance against chemical and biological breakdown, and overall functional stability – focusing on the possibility of exceeding 100 years lifetime. Regarding the pipes' mechanical stability, it was concluded that the pipes' deflection would never exceed more than 15% within 100 years for pipes of stiffness class SN4 and higher for pipes that have been installed in a regular way. For worse burying conditions (e.g., loose or inhomogeneous, not well-packed clay), a higher stiffness class of 8 or 16 kPa should be considered. This means that the creep does not become critical within the 100-year period. The long-term material strength is secured if the bending strain is constant (the stress relaxation exists) and the pipe's material stabilization system is intact. Then, for normal operating temperatures up to 20°C, the pipe will function for at least 100 years. Chemicals and detergents that are present in sewer water do not harm the integrity of the pipe material and system due to the intrinsic property of the polymers and due to the stabilizers ensuring chemical stability safely for 100 years. Regarding the biological breakdown, it was stated that using plastic pipes for 50 years in favourable environments for bacteriological growth did not show any development of cultures that break down plastics. Thus, the safe operation can be assumed for a lifetime of 100 years. The final conclusion was that everything points towards at least 100 years of service life for buried sewer pipes made of today's high-quality virgin PVC and PE resins if the pipes are installed and used in accordance with the standards.

In 2003, PPI (Plastics Pipe Institute) members [64] revealed a technical report focused on the lifetime of corrugated HDPE pipes. The main conclusion was that there is considerable supporting justification for assuming a 100-year or greater design service life for corrugated PE pipe when properly used and reasonably well installed. Additionally, minimum material design values for tensile strength (both short and long-term) were stated.

In 2005, Husan and McGrath [65] reported a Protocol for Predicting the Long-term Service of Corrugated HDPE Pipes. The data was later partially presented by Pluimer [66]. This study was initiated to determine requirements for assuring that corrugated HDPE pipe will provide a 100-year service life. It was demonstrated that tensile stresses are relatively low when pipe installation meets typical requirements and maintains changes in vertical diameter to less than 5%. Long-term tensile strain for the service condition should be less than 2.5%, corresponding to a long-term stress of approximately 3.4 MPa with an applied safety factor of 1.5. The general recommendation for the minimum depth of fill is larger than 0.6 m or one-half of the pipe diameter. Additionally, four long-term material properties of HDPE corrugated pipes were investigated, including stress cracking resistance of the pipe, antioxidant lifetime of the pipe, long-term tensile strength, and long-term flexural modulus. For each property, a set of tests at different temperatures and/or stresses shall be performed so that the 100-year behaviour of the pipe at a site temperature of 23°C can be extrapolated and determined with confidence.

In 2006, Bergström et al. [67] studied the behaviour of plastic pipes made of generic HDPE, PP-B, PP-HM materials under constant strain conditions caused by up to 45% pipe deflection. For the HDPE material, it had been demonstrated that even under stress relaxation conditions, the stress is sufficient to both initiate and propagate cracks through the pipe wall. It was stated that the high-stiffness HDPE material is clearly unsuitable for use in pipes exposed to long-term deflection. For filled PP-B material the damage developed as an area of craze that did not penetrate the pipe wall, instead of the single crack brittle failure in the PE material. For PP-HM, the only damage observed was stress whitening. The performed analysis confirmed that although the materials relax continuously, substantial stresses remain after 50 to 100 years of service.

In 2008, Breen [68] reported experimental measurements of deformation, surface roughness, and inner surface degradation assessment performed on six different sewage PVC pipes operating between 20 and 30 years in the Netherlands. These results were partially published by Meerman in [69]. The pipes showed signs of operation - scratches and some abrasion, which can be attributed to the transport of abrasive compounds, for example sand particles. No chemical degradation of attack by aggressive solvent was observed in the parts studied. Based on the residual stress measurement (3 MPa) and estimation of soil loading (3 MPa), no craze initiation and crack growth are expected. The performed investigations confirmed that the lifetime of PVC pipe systems would exceed 100 years under most service conditions.

In 2013, Gould et al. [70] analyzed the premature failure of a PVC-U sewer rising main that had been operating for 34 years, even though the lifetime expectancy was more than 100 years. Microscopy and fracture surface investigation identified the origin of the fracture as a foreign inclusion in the middle of the pipe wall. A large number of similar defects were also identified remote from the failure location. Additionally, based on the outcome of performed analyses, it was reasoned that no material degradation had occurred in contact with domestic sewage. The final conclusion was that for older PVC-U sewer pipelines, while material durability is certainly not compromised from contact with domestic sewage, service failure can (and does) occur by fracture from inclusions that were "built-in" during original manufacture.

In 2016, Meijering et al. [8] published a comprehensive technical report focused on 100-year service life of PP and PE gravity sewer pipes. The results were partially summarized in 2014 in a conference paper [71]. It was concluded that using qualified polyolefin materials and pipes that are well extruded and installed according to good workmanship practice and standards, the test results of the 5 excavated PE and PP-B pipes have shown that polyolefin pipes are well qualified to reach a 100-year lifetime. Even for the first-generation PE (studied after 38 years in use) and PP-B (studied after 23 years in use) no significant reduction of mechanical properties and stabilization was shown.

For further studies (or new pipes), the lifetime of 100 years for non-pressure sewage pipes manufactured from PE and PP-B can be expected if the pipes meet the requirements of European product and system standards EN1852 [55] for PP, EN12666 [54] for PE and EN13476 [57] for structured wall pipes. Additionally, requirements for material (thermos-oxidative degradation, max allowed stresses), pipe (hydrostatic and relaxation tests with microscopic analysis), and installation (according to CEN/TR 1046 [72] and Teppfa study [73]) have been determined.

In 2021, Khanh et al. [74] studied the slow crack growth resistance of corrugated HDPE pipes used for infrastructure applications. The slow crack growth tests were performed on the pipe liner in water at three different combinations of pressure/temperature of 4.5 MPa/80°C, 3.1 MPa psi/80°C, and 4.5 MPa/70°C. The results were then extrapolated by the Rate Process Method (developed from the Arrhenius principle of time-temperature superposition). It was concluded that at the service conditions of these HDPE corrugated pipes (3.4 MPa and 10°C), the 100-year service life is met.

4.3 Conclusions

Contrary to pressurized plastic pipes, for non-pressure pipes there are no tests in place defining design life. The standards only define mechanical, physical, chemical, and other properties that the material and pipes should have and experimental measurements that the material and pipes should pass.

In non-pressure pipes, the dominant loading is caused by the weight of the soil. Therefore, the burying conditions are essential to secure safe long-term operation. Bad burying conditions (e.g., loose or inhomogeneous, not well-packed clay) may result in higher pipe deflection and greater susceptibility to creep damage. Based on the reviewed studies, the substances (chemicals and detergents) presented in sewer water seem harmless to pipe materials due to the stabilizers ensuring chemical stability safety for more than 100 years. Additionally, excavated pipes operating for up to 38 years showed no reduction in mechanical properties.

The study of published plastic pipe research focused on non-pressure pipes concludes that correctly installed and operated PVC, PP and PE pipes put on the market today will have a service life exceeding 100 years.

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