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100 Year Service Life of Polypropylene And Polyethylene Gravity Sewer Pipes

A TEPPFA Project in cooperation with Borealis and LyondellBasell

Full Technical Report

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100 years service-lifetime prediction of Polyolefin gravity sewer systems

Foreword

The prediction of the in service-lifetime of gravity sewer pipes made from polyolefin materials has been discussed for many years without a clear answer becoming available. The outcome of this project is therefore considered to be vitally important for material suppliers, pipe manufacturers and the designers and operators of sewer systems .

This project has been carried out in cooperation between The European Plastic Pipes and Fittings Association (Teppfa) and the material suppliers LyondellBasell and Borealis and reviewed by the independent external expert, professor Heinz Dragaun

The outcome of the project is that a 100 years in service-lifetime can now be confidently predicted for products that fulfil the requirements of the applicable EN product standards supported by additional long term testing and appropriate installation requirements.

The project partners wish to acknowledge professor Heinz Dragaun for his excellent contribution to this project and his supportive contributions to the report

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100 years service-lifetime prediction of Polyolefin gravity sewer systems

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1. Introduction and summary

1.1 Introduction

The prediction of the life expectancy of plastic pipe systems is well documented for pressure applications, where stresses in the pipe wall are acting continuously. Hydrostatic tests at different temperatures allow us with Arrhenius extrapolations to make a reliable estimate of the predicted lifetime at specific pressure and temperature ranges.

For non-pressure applications in sewage and drainage where pipes are installed and operate without internal pressures, a continuous deflection and subsequently a constant strain loading applies. Also for this application a lot of literature can be found where the experience and performance of polyolefin pipes have been investigated. However, in the current international product standards for non-pressure sewage pipes manufactured from PE or PP no reference has been made to the predicted lifetime of these pipes. A scientific approach to estimate the lifetime of these pipes and materials in non-pressure applications is not available and no adequate test methods are defined. In daily practice it becomes increasingly important to provide more exact evidence of the predicted lifetime. This study aims to provide sufficient validated data to enable an in-service life expectancy of at least 100 years to be declared for polyolefin (PE and PP) sewer pipes. The study covers PE and PP pipes produced according to EN 1852 [5], EN 12666 [4] and Type B pipes of EN 13476-3 [6].

1.2 Summary and conclusions

To demonstrate the long term performance of sewer pipes, solid wall and structured-wall, made from PE and PP, the following items have been analyzed and investigated:

- a. Collection of evidence and providing conditions of sufficient long term resistance to thermo-oxidative degradation of the used materials. Based on test data from hydrostatic pressure tests and MRS evaluation and Arrhenius extrapolation, the allowable stresses and the related test requirements have been evaluated.
- b. The long term behavior under constant strain loading of non-pressure sewer pipes have been analyzed and based on relaxation tests, calculations have been made for the prediction of the long term stresses and estimations have been made regarding the risk of pipe failure under constant deflection at long term.
- c. The possible effect on the lifetime prediction of sewer water composition and the temperature of the sewer water have been evaluated
- d. Excavation projects have been executed to analyze the remaining quality of the sewer pipes after a period of operation and the prediction of remaining lifetime of these pipes.
- e. The whole test program and the results has been reviewed and validated by an independent third party authority

In this study, it has been demonstrated that a 100 years lifetime for non-pressure sewage pipes of PE and PP can be expected, provided some basic conditions are met:

- The resistance to thermo-oxidative degradation of the resins used has been proven under the conditions described in this report
- The allowable stresses at long term are not continuously exceeding the defined levels at the operating temperatures
- The resins from which the pipes are made fulfill the basic requirements as defined in the products standards; hydrostatic tests at elevated temperatures during 1000 h to demonstrate the resistance to slow crack growth
- The pipes have to be made according to accepted high level of production practices and meeting all requirements of the product standards
- The pipes have to be installed according to the relevant standard (CEN/TR 1046)[21] and the recommendations of the Teppfa study "Buried Pipes"- [15] referenced in this report.
- For PE and PP the long term pipe deflection in service shall be below 8 %.
- The design of structured-wall pipes needs to avoid excessive stress concentrations. It is recommended to require compliance with the 30 % ring flexibility test in the products standards for structured wall pipes in order to show the performance and stability of the wall construction at short term. The 30 % Ring flexibility test together with the impact test as defined in the product standards are adequate and selective tests to avoid too high stress concentrations and bad welding lines between the 2 layers of type B structured-wall pipe.
- The relaxation test as described in this study shall be added to future versions of the relevant product standards to prove the long term stability of the material and the wall construction as well as the long term resistance to stress cracking.

In this study, it has been demonstrated that a 100 years lifetime for non-pressure sewage pipes manufactured from PE and PP-B can be expected, provided that the following conditions are met:

- a. The pipes shall meet the requirements of European product and system standards EN1852 for PP, EN12666 for PE and EN13476 for Structured Wall Pipes of PE and PP, and
- b. The material, pipes and installation shall meet the requirements specified in table 1.1

Table 1.1. Requirements for sewer pipes and materials to prove the 100 years lifetime

Material requirements	Thermo-oxidative degradation ¹⁾	PE: 95 °C, $\sigma = 1.0$ MPa PP: 110 °C, $\sigma = 1.0$ MPa	> 8760 h > 8760 h
	Max. allowable stresses derived from the available reference curves ²⁾	45 °C: PE, $\sigma = 5.3$ MPa ³⁾ PP, $\sigma = 3.9$ MPa ⁵⁾ 23 °C: PE, $\sigma = 7.4$ MPa ³⁾ PP, $\sigma = 7.9$ MPa ⁴⁾	100 years 100 years 100 years 100 years
Pipe requirements	Hydrostatic tests EN 12666 and EN 1852	PE: 80 °C, $\sigma = 2.8$ MPa PP: 95 °C, $\sigma = 2.5$ MPa	1000 h 1000 h
	Product requirement acc. to EN 13476	Ring flexibility	30 %
	Relaxation tests	PE & PP: Acc. to Janson [14]	≥ 4000 h at 15 % deflection
	Microscopic analysis of the strained pipe samples	PE & PP: At the end of ≥ 4000 h Janson test	No crack initiation, no cracks or other damages
Installation requirements	Pipe installation	Acc. to CEN/TR 1046 [21] Acc. to Teppfa study [15]	Moderate or Well compaction Standard proctor >87 %
	Maximum pipe deflection at commissioning	Acc. to CEN/TR 1046 [21]	Max. 8 %

Legend:

- 1) Test conditions based on these experimental data, the prediction of 100 years service-lifetime with regard to the resistance to thermo-oxidative degradation can be assured.
- 2) The calculated stresses for 45 °C at 100 years lifetime assumes for
 - PE, that no second branch after 50 years appears.
 - PP-B, that no third branch (thermo-oxidative degradation) after 50 years appears.
- 3) Hoop-stress calculated acc. to ISO 15494 [12], Annex B, paragraph B.1.2, Equation B.2 for PE 80
- 4) Hoop-stress calculated acc. to ISO 15494, Annex E, paragraph E.1.2, Equation E.6 for PP-B (first branch)
- 5) Hoop-stress calculated acc. to ISO 15494, Annex E, paragraph E.1.2, Equation E.6 for PP-B (second branch)

An analysis has been made of the remaining stresses after long term operation.

For that purpose, a set of relaxation tests have been executed, measuring the relaxation modulus as function of loading time. Extrapolation of these data up to 100 years provide information about the remaining stress after relaxation.

From the test results [Annex: 1,5], it can be seen that in all cases, virgin and excavated pipes, the line for Compliance versus log time shows a straight line until 13270 h test duration which demonstrates a stable pipe material and pipe wall where a straight relaxation behaviour may be expected and allowing extrapolation these data to 100 years.

Calculated stress of SN8 pipes after relaxation at long term (100 years), by 8 % and 15 % deflection at 23 °C, are shown in table 1.2.

Table 1.2. Calculated stresses of SN8 pipes by 8 % and 15 % deflection

At deflection of	Stress after 4000 h		Stress after 13270 h		Stress after 100 years	
	8 %	15 %	8 %	15 %	8 %	15 %
PP 110mm solid wall	3.37	4.87	2.88	4.15	2.05	2.95
PP 160mm structured-wall	4.79	6.91	4.21	6.06	3.17	4.57
PE 200mm solid wall	3.74	5.40	3.47	5.01	3.01	4.34

So, at a maximum deflection of 8 % the long term stresses are well below the critical values. A maximum deflection of 15 % of structured wall pipes becomes more critical. However, relaxation tests conducted at 15 % deflection over 13270 h have demonstrated that the pipes relax in a regular way without unstable deviations, indicating that no failure would be expected. It has been found that in solid wall pipes at 15 % deflection, the (relaxed) stress is already lower than the long term allowable stress within 24 h and for structured-wall pipes is this the case already after 1000 h relaxation time. At 8 % deflection of the structured-wall pipe also already after 24 h relaxation time the stresses are below the allowable stress. Also the relaxation tests carried out on excavated pipes show a continuous relaxation pattern. In the reported test results, extrapolation to 100 years has been proven to be valid. In view of the remaining stresses, it is recommended that deflections of more than 8% should be avoided.

At 5 sites, pipes which have already been in service for long periods have been excavated and samples taken for a test program to be carried out.

- PE solid wall pipes 200mm SN8 excavated in Finland,
- PE solid wall pipes 280mm and 355mm SN8 excavated in Germany,
- PP-B solid wall pipes 110mm SN8 excavated in Norway and
- PP-B structured-wall pipes 160mm SN6.3 (double wall pipe) excavated in Norway
- PP-B structured-wall pipes 200mm SN8 (Ribbed pipe) excavated in Denmark

Even for PE of the first generation it has been demonstrated that after 38 years of operational use, a total lifetime approaching 100 years can be expected. This outcome is supported by other recent investigations, indicating that non-pressure sewage pipes do not behave differently from the pressure pipes of the same period [16], where it has been concluded that after a service time of 30 years at least a remaining lifetime of 50 years is predicted. Other excavated pipes (PP-B) had an operation time between 10 and 23 years.

All excavated pipes, PE and PP-B, have shown a very good test result without reduction of quality aspects.

- Physical characteristics (OIT, Intrinsic viscosity, MFR, density, melting point, tensile properties, elongation at break), all in the range of the old PE63 data sheets
- GPC, no accelerated polymer degradation found due to sewer water attack

- Pressure tests, $\sigma = 2.8$ MPa at 80 °C on 200mm PE pipes, failure times resp. 584 h, 417 h, 1034 h which are similar results as published of original PE63 pipes of the first generation
- Pressure tests, $\sigma = 2.5$ MPa at 95 °C on 110mm PP-B pipes, failure times resp. 1260 h and 2x >2800 h, which is much longer than the original requirements (>1000 h)
- Deflection after excavation, ~1.5 % for PE pipes 200, 280 and 355mm
- Deflection after excavation, 1.6 - 2.0 % for PP-B pipes, solid wall and structured wall
- Residual ageing resistance (PE), residual lifetime of more than 50 years has been calculated
- Ring flexibility and impact test at -10 °C of PP-B pipes, solid wall and structured-wall, meet the today's requirements

Analysis of the composition of sewer water resulted in a conclusion that no effect on the lifetime of pipes can be expected. In this report, the behavior at a continuous maximum temperature of 45 °C has been evaluated. This is based on the guidance from EN476 where the suitability for a continuous discharge temperature of 45 °C has been required for diameters ≤ 200 mm and 35 °C for diameters > 200 mm. Our investigations have shown that in practice under various situations the temperature does not exceed 30 °C. This means that a significantly higher safety has been included in our approach. In view of actual temperatures occurring, the stresses in the pipes are far below critical values.

(note: diameters ≤ 200 mm are mostly used in house connections where diameters > 200 mm are used as sewer mains where the temperature in practice is even lower)

Remark: *The analysis and predictions are valid for virgin materials. Modified materials, like foamed materials and mineral filled materials are not covered by the outcome of this report.*

Final statement from Project Reviewer, professor Heinz Dragaun

“100-years-service-lifetime prediction of Polyolefin gravity sewer systems”

I consider this project to be very relevant to improving knowledge of the in-service performance of polyolefin sewer systems all over the world.

As an experienced person in the field of testing plastics pipes at the “TGM-Versuchsanstalt - Federal Institute of Technology, Department Plastics Technology and Environmental Engineering”, Vienna since 1975, I was invited as an independent expert to review and comment on the work which was carried out for this project over the last 3 years.

Summarizing it is to say a lot of investigations were conducted - both on material data and also in the area of functional performance in the field - on pipe samples not only from new production but also older materials which were excavated after long term practical application from different European countries (some which have been in service for almost 40 years)

All test methods used were executed in accordance with valid International Standards (ISO) and the actual knowledge of science in polymer materials.

The investigations were carried out on classical solid wall pipes (monolayer and multilayer) and also on so called geometrical structured wall pipes, which is a more recent innovation.

In my opinion the project has been conducted in a proper and scientifically reliable way with close cooperation between material producers and pipe and fitting producers with the target of demonstrating how long time service quality can be achieved in the field of Polyethylene (PE) and Polypropylene (PP) gravity sewer systems.

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2. Theoretical considerations for the prediction of a 100 years lifetime under service conditions

The specifications of non-pressure solid and structured wall pipes made from Polyethylene (PE) or Polypropylene (PP) are laid down in several national and international standards [1,2,3,4,5,6]. However they do not describe an extrapolation method whereby the long-term behaviour of non-pressure pipes under service conditions can be determined in accelerated ageing tests.

It is widely accepted that due to chemical degradation of the polymer the dominating fracture mechanism in non-pressure pipes is a brittle failure mode. To achieve a 100 years service-lifetime it has to be evident that non-pressure pipes do resist premature failures caused by thermo-oxidative degradation.

2.1 Long-term resistance to thermo-oxidative degradation

The auto-oxidation of PE and PP is well understood [7,8]. When initiated the rate determining step might be either the formation of chain radicals via hydrogen abstraction or at least chain scission. It is well proven that the kinetics of the ageing process follows Arrhenius equation which quantitatively describes the relationship between the rate of the degradation reaction and temperature.

$$\text{Arrhenius equation} \quad k = \text{const} \cdot \exp\left(-\frac{E_A}{RT}\right)$$

Whereas k is the rate of the degradation reaction at temperature T , E_A is the energy barrier which has to overcome and is the so-called activation energy of the ageing process, T is the absolute temperature in degrees Kelvin and R is the gas constant.

Since the introduction of plastic pipes made from PE and PP in pressurized applications, suitable accelerating test methods were needed to predict the maximum service lifetime of those pipes under multi-stress conditions (e.g. temperature, pressure, fluid and/or thermal degradation). It was recognized very early on that hydrostatic pressure tests on pipes at different internal stress load and temperatures can be used as a reliable and proven method to estimate the service lifetime either by graphical [9] or today by mathematical extrapolation based on the Arrhenius equation as described in ISO 9080 [10]. Those creep rupture curves of Polyolefin pipes according to ISO 9080 indicate different failure modes: In phase I ductile fractures occur due to yielding, whereas in phase II brittle fractures are dominating, which are mainly related to slow crack growth. And phase III limits the lifetime of the pipes by the extreme brittleness of the degrading polymer even under low stress levels (figure 2.1).

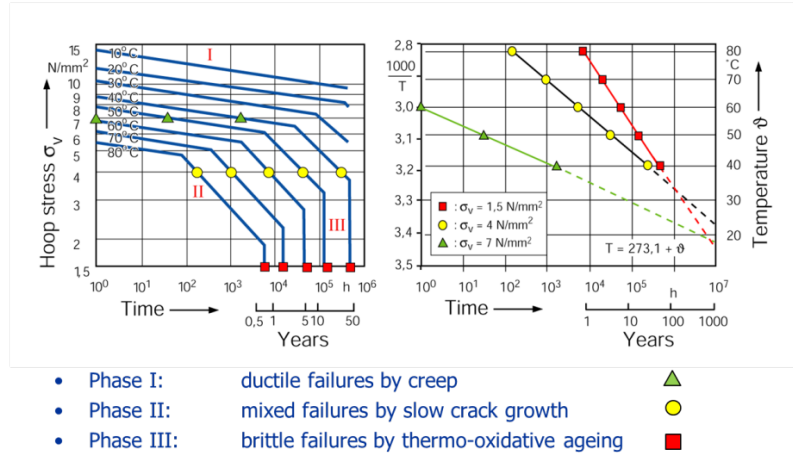


Figure 2.1: Principle of a Creep Rupture Diagram and Arrhenius Evaluation

The activation energy E_A for each phase can be determined from the slope of an Arrhenius-plot as a function of the experimentally obtained fracture times at equivalent internal stress loads versus the reciprocal ageing temperatures as illustrated in figure 1 or from a logarithmic form of the Arrhenius equation:

$$E_A = 1,9152 \cdot 10^{-2} \frac{\log(t_1 / t_2)}{\frac{1}{T_1} - \frac{1}{T_2}} \frac{\text{kJ}}{\text{mol}}$$

E_A	Activation energy [kJ/mol]
t_1, t_2	Time to failure at temperature T_1, T_2
T_1, T_2	Absolute temperature [°K]

It is common practice to perform durability tests at elevated temperatures to accelerate ageing and to estimate the theoretical lifetime at service conditions based on Arrhenius equation. An example of such a lifetime prediction methodology is given in ISO 9080, pos. 5.1.4 and 5.2 for pressure pipes. It seems practicable to adopt the extrapolation rules postulated in ISO 9080 for a 100 years lifetime prediction of non-pressure pipes. As a consequence the accelerated ageing tests for non-pressure pipes should be performed at minimum 50 °C higher temperatures above the service temperature and at least last for minimum 8760 h (= 1 year) without brittle failures to achieve an extrapolation time factor ke of 100 (years) as described in ISO 9080, pos. 5.2.

As specified in EN 476 [1] sewer systems have to be suitable for constant water-flow and maximum water temperatures of 45 °C (pipe dimension \leq DN200) or 35 °C (pipe dimension \geq DN200) respectively. It is considered by Teppfa that the 100 years service-lifetime prediction shall be evidenced for a constant water temperature of 45 °C for all pipe dimensions to cover the most severe condition. Therefore the lowest applicable ageing temperature for non-pressure Polyolefin pipes is 95 °C, if their apparent activation energy E_A of the ageing process is greater than 90 kJ which has been experimentally verified! This has been proven for the recommended PE grades in this study.

The minimum activation energy E_A of 90 kJ/mol results from exerting the following parameters: Time to failure $t_1 = 1$ year at 95 °C and $t_2 = 100$ years at 45 °C; temperature $T_1 = 368$ K (95 °C) and $T_2 = 318$ K (45 °C) in the logarithmic form of the Arrhenius equation:

$$E_A = 1,9152 \cdot 10^{-2} \frac{\log(t_1/t_2)}{1/T_1 - 1/T_2} = 1,9152 \cdot 10^{-2} \frac{\log(1/100)}{1/368 - 1/318} = 89,6 \text{ kJ/mol}$$

If the apparent activation energy E_A is lower than 90 kJ/mol, as expected for PP resins then higher ageing temperatures are required (see table 2.1) to avoid longer ageing times. Preliminarily experimental results indicate that the apparent activation energy E_A for PP-B resins is in the range of 75 – 85 kJ/mol.

Table 2.1: Calculated minimum activation energies E_A to achieve a 100 years lifetime at $T = 45$ °C

$\Delta T = T_{\text{Ageing}} - T_{\text{Service}}$ in °C	Minimum E_A in kJ/mol
40	109
50	89.6
60	76.7
70	67.5

As a consequence Polyolefin materials have to demonstrate their resistance to thermo-oxidative degradation in pipe tests at conditions:

PE: 8760 h (1 year) /95 °C at 1.0 MPa Type of test : Water/Water (internal/external)

PP: 8760 h (1 year) /110 °C at 1.0 MPa Type of test: Water/Air (internal/external)

Hydrostatic pressure tests on pipes are well established and the time to failure can be easily determined due to the resulting pressure drop and water leakage when brittle failures occur. Pipe pressure tests are already implemented in the relevant standards for non-pressure PE and PP-B pipes. Furthermore the time to failure of brittle fractures due to the degradation of the polymer are quite independent from the applied internal stress level as shown in figure 2.2. Slightly shorter failure time at 1.0 MPa for PE and PP-B compared to the extrapolated failure time at 0.0 MPa can be seen as a necessary safety factor for a more reliable lifetime prediction.

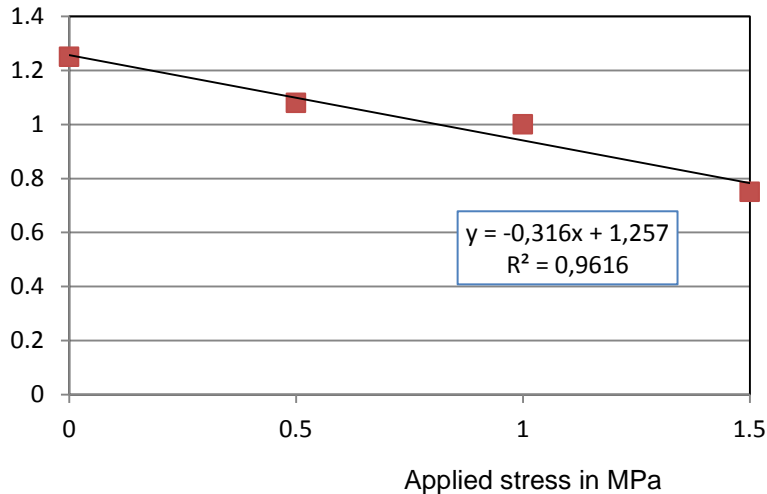


Figure 2.2: Normalized time to failure as a function of applied stress

The recommended PE and PP grades for non-pressure pipe applications shall surpass the requirements acc. to table 2.2. A comparatively low stress level, $\sigma = 1.0$ MPa, is sufficient to determine the resistance to thermo-oxidative degradation and to extrapolate to the expected 100 years lifetime.

Table 2.2: Thermo-oxidative degradation requirements and test conditions

Material	Test condition	Requirements
PE	Temperature : 95 °C Hoop stress : 1.0 MPa Type of test : Water-in-Water	> 8760 h
PP-B	Temperature : 110 °C Hoop stress : 1.0 MPa Type of test : Water-in-air	> 8760 h

2.2 Long-term mechanical integrity

Another important aspect that has to be considered is the long-term mechanical integrity of solid- and structured-wall non-pressure pipes. The effects of stresses and notches in deflected buried pipes under normal soil conditions and residual stresses from the pipe extrusion process must be estimated. Based on hydrostatic test results regression curves are well understood and have been evaluated and on that basis, the long term behavior of pipes under constant stress can be estimated. However, this existing data has to be interpreted in the constant deflection condition which is the practice for sewer pipes. A sufficient resistance towards constant deflection and slow crack growth has to be demonstrated. In non-pressure pipes, the constant deflection generates a strain which is constant at long term. This loading regime and the lifetime estimation under this condition is evaluated in this study.

Regarding the quality and the expected performance of the installed sewer system, the whole production chain from raw material to installation and operation must meet the requirements for good workmanship. This is a crucial basic condition for a reliable lifetime estimation.

Only qualified raw materials with a good level of stabilisation, meeting the requirements as in clause 1 is covered by the outcome of this study.

It is also an important condition that pipe design and production processes has to meet the highest standard making it possible to realise the intrinsic and intended performance level of the raw material used. This means that pipe wall design, in particular for structured-wall pipes, should not cause too high stresses and strains that could cause cracking and premature failure. Pipe production processing is assumed to be optimal. Pipes need to meet the requirements of the relevant product standards.

If internal stresses and strains exceed a certain level, there will be a risk of brittle failures due to slow-crack-growth (SCG). It is obvious, that initial stresses will relax with time, yet it has to be proven that the remaining stresses and strains will not cause premature brittle failures.

Finally, a good performance of the pipes can only be achieved by a careful installation practice meeting the requirements of CEN/TR 1046 [21] and the recommendations of the Teppfa study [15]. Installed pipes that do not meet these conditions are not covered by the outcome of this study.

2.2.1 Lifetime estimation under constant stress

The maximum allowable stresses in non-pressure pipes to assure a 100-years-service lifetime, especially for structured-wall constructions must be evaluated.

The relevant standards for solid- and structured-wall non-pressure Polyolefin pipes do not provide a calculation of the maximum allowable stresses at 45 °C and 100 years lifetime, because they do not specify the long-term temperature/stress behavior. From the reference lines given in the pressure pipe standards for PE and PP the maximum allowable stresses to meet 100-years lifetime can be calculated (see table 2.3).

Table 2.3: Maximum allowable stresses at 100 years lifetime, calculated from the reference lines given in ISO 15494 [12]

Polyolefin Grade	Stress in MPa (45 °C / 100 years)	Stress in MPa (30 °C / 100 years)	Stress in MPa (23 °C / 100 years)
PE	5.2	6.6	7.4
PP	3.9	6.9	7.9

The calculated maximum allowable stresses clearly indicate that PE and PP materials following the requirements given in Table 1.1 offer the best performance in regard to slow crack growth resistance. The resistance to slow crack growth within a 100 years service-lifetime can be assured.

2.2.2 Lifetime estimation under constant strain

In practice, the loading regime of non-pressure sewage pipes is not a 'constant stress' but a 'constant strain'. When installing a pipe, after a limited time (max. 2 years) the deflection of the pipe remains constant and consequently also the strains in the pipe wall.

In this report, the approach and experience of L-E. Janson [14] has been evaluated and will be the basis for the lifetime estimation in non-pressure sewage applications where the deflections of the pipes are constant and consequently the strain is constant where the related stresses will reduce due to a relaxation process.

Also the recommended practises for installation of piping systems and the allowable deflections as defined in CEN/TR 1046 [21] are the basis for our approach.

The used material parameters can be found in CEN/TS 15223 [22]

For the performance of pipes under practical conditions, reference is made to the Teppfa study [15]. The design graph published in that study (figure 2.3) represents experience and measurements in practice during several decades and is considered as indicative for the real deflections in practice.

2.2.3 Predictable deflections

In the Teppfa [15] project it has been demonstrated that with the preferred stiffness classes SN4 and SN8, the predicted deflection at 100 years remains well below the 8 % in case of good and moderate compaction of the backfill in the trench. (Figure 2.3) This quality level of installation is in most cases common practice and does not cause excessive or extra installation costs.

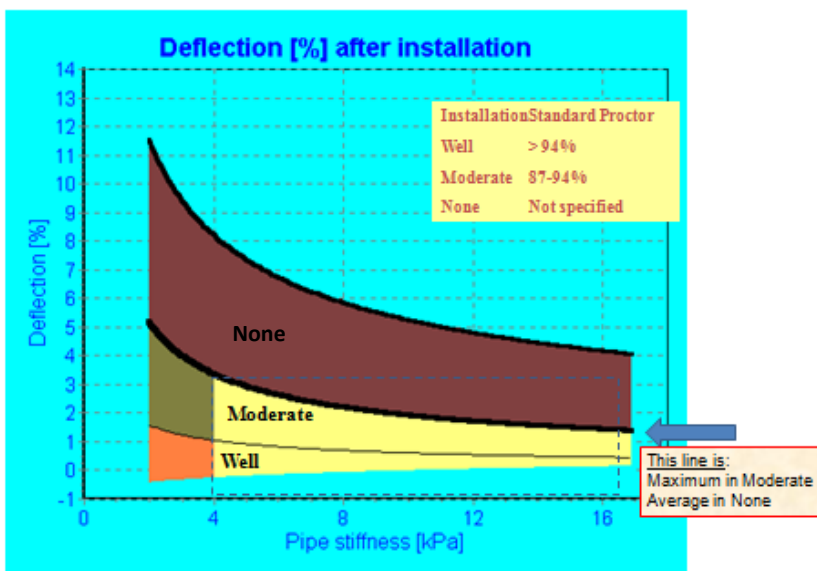


Figure 2.3 Teppfa design graph for installed flexible pipes

During installation, a certain initial deflection will occur, depending on the soil compaction in the trench (see figure 2.4). After installation of the pipe, a process of soil settlement takes place

resulting in ongoing deflection; the flexible pipe is simply following the soil movement. This soil settlement is normally finished after maximum 2 years. Also the effect of additional traffic load is shown to accelerate soil settlement causing the final level of deflection earlier. After that time, the ongoing deflection until 100 years is negligible. In the Teppfa project [15] mentioned earlier it can be seen that in the case of 'Well' compaction during installation, the final deflection is reached within a period of some weeks or months. This means that from that moment on, a pure constant deflection and consequently a constant strain acts in the pipe wall. Due to relaxation, the stresses are reduced in time following a predictable pattern

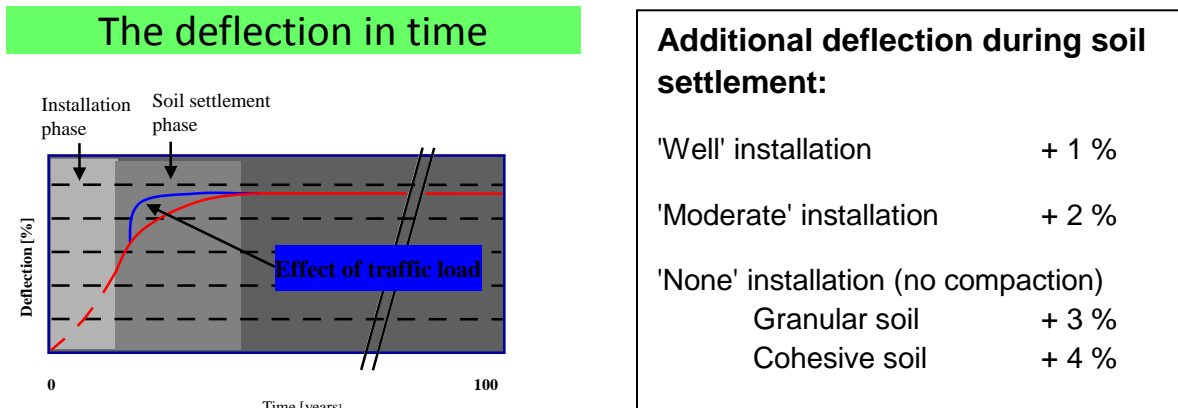


Figure 2.4 The pipe deflection during installation and soil settlement

During the installation phase the initial deflection is realised as given in the design graph in figure 2.3. In this design graph the spread in initial deflection after installation is given for the different quality of soil compaction.

It is assumed that in practice installation is carried out in at least a moderate way (see design graph). The lines in the graph indicate the maximum of a certain compaction class and the average of the next worse compaction class; e.g. the maximum deflection line of moderate installation is the same as the average of the "none compaction" class (brown area).

In the Teppfa "Buried Pipes" study [15], it has been shown that this design graph has been confirmed by using many data bases from other projects, demonstrating that the reliability of this design graph is very high.

From this design graph, the predicted deflections under moderate compaction of the soil, can be found:

Deflection:	After installation	After soil settlement
SN4	3.5 %	5.5 %
SN8	2.5 %	4.5 %

From this design graph, it also can be seen that in good (Well and Moderate) installation practises, the initial deflection will be no more than 2-4 % and after the soil settlement has been completed up to 6 %. By assuming a maximum long term deflection of 8 %, our calculations include a significant safety factor; our calculated stress data after relaxation (see clause 2.2.8) show at least values of 40 % higher than in real practice.

There are two reasons why the condition of a maximum allowable deflection of the pipe of 8 % at long term (100 years) was assumed. It is required in CEN/TR 1046 and it is a basis for good workmanship of the installer, avoiding excessive point loads and subsequent high local stresses and strains that could cause premature failure.

2.2.4 Strain calculations

To calculate the remaining stresses at long term, the real strains in the pipe wall and the relaxation modulus must be known. The strain ϵ in the outer layer of a pipe with a given deflection can be calculated as follows:

$$\epsilon = F_d * (\delta/D_n) * (2*e/D_n) \quad \text{and the stress: } \sigma(t) = \epsilon * E(t)$$

where F_d is a constant factor related to the loading condition(see later), δ is the diametric deflection and D_n is the diameter of the pipe at the neutral axis, e is the distance from the outer layer to the neutral axis. The actual stresses in the pipe are time dependent due to the relaxation process. So $\sigma(t)$ is the actual stress at time t and $E(t)$ is the relaxation modulus at that time. The deflection of the pipe is mainly determined by the effective ground load, the level of support of the surrounding ground as result of the quality of backfilling and the reaction of the pipe which depends on the dimensions and the stiffness of the pipe.

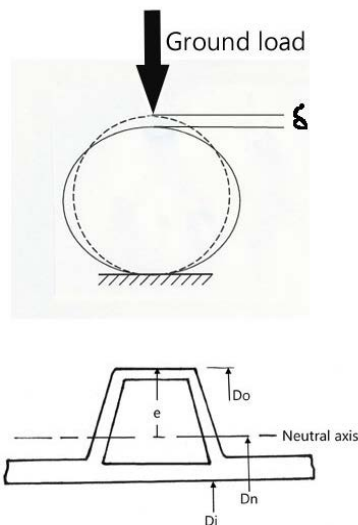


Figure 2.5 Pipe deflection by external loads

In general, flexible plastic pipes follow the settlement of the soil after installation.

The factor F_d is chosen arbitrarily and depends of the type of loading. A factor 3 is chosen in case there is an oval deflection of the pipe. This deflection pattern can be expected when the

installation of the pipes is carried out in the recommended way, where a well or moderate compaction has been applied and the pipe is well supported by the soil. A factor 4.28 is normally used when there is a pure deflection between 2 flat plates as it is the case in a laboratory test. A factor 6 is sometimes recommended to calculate strains in case of specific point loading which will be avoided by good installation practises.

The parameter "e" is the distance to the neutral axis. In the case of a solid wall pipe the neutral axis is the same as the average diameter and e is half the wall thickness. In structured wall pipes, the value of e is much larger. In this study, strains are calculated in the most extreme situations: at the outer layer of the corrugations (or ribs).

This formulae for the calculation of the strain at any point also explains that for the same deflection, the strain and stress is higher for the thicker pipes of the same diameter.

2.2.5 Strainability and failure

Where in a constant stress loading the lifetime of pipe materials can reliably be calculated based on recognized theories, however for a constant strain loading it is not so simple. Nevertheless, there is a lot of scientific data and experiences reported in literature regarding the material and pipe behaviour under constant strain. For a reliable lifetime prediction, the approach of Janson [14] has been used as a key ingredient.

Without repeating all details, the interpretation of his work and theories for constant strain loading and subsequent stress relaxation behaviour, can be summarized as follows:

- In a constant strain condition the remaining stress is not the determining factor for failure, but the strainability of the (pipe) material should be considered as failure criteria.
- Stress relaxation process as such contributes to the fact that failure is unlikely to occur
- If no failure occurs in short time (e.g. within 4000 h), then it is unlikely that it will ever occur
- Long term allowable strains are proposed: 5 % for PE and PP.

Note from Janson:

Above statements are based on the fact that only well-processed pipes and high quality resins are used (i.e. resins fulfilling requirements according to Table 1.1) and the pipes are installed under good installation practises according to the standards. This implies that these materials are successfully passing the relevant long term tests and the chemical stabilisation system is still intact. In the summary of this report an overview is given of all the necessary quality requirements

Based on the fact that that comparatively high local stresses may be present in the pipe profile during the first months of the installation due to soil conditions, compare 2.2.8, 2.2.9 and 2.3 below, the requirement on a visual inspection for cracks and failures has been included in the test requirements. The visual inspection is done on the strained pipe samples at the end of the Janson test period as specified in Table 1.1, i.e. at testing times of 4000 h or longer. This is a necessary complement to the strainability approach by Janson [14] in order to secure, particularly for structured-wall pipes and for positions in the pipe design identified as critical regarding high stresses, see 2.3 below, that stresses locally have relaxed below the max allowable stresses without any premature failure, crack initiation or other type of damage in the

pipe design. The test procedure is also important to prove the good quality of the welding line between the two layers in type B pipes.

2.2.6 Relaxation behaviour

When a pipe is buried what normally results in a constant deflection of the pipe, the bending strains in the pipe are constant and consequently, the stresses will decrease in time, the well-known stress relaxation behaviour of plastics pipes.

For demonstrating the long term behaviour of non-pressure pipes, Janson emphasizes the importance of analysing the relaxation behaviour as a function of time.

As an example, relaxation curves used by Janson are shown in figure 2.6.1.

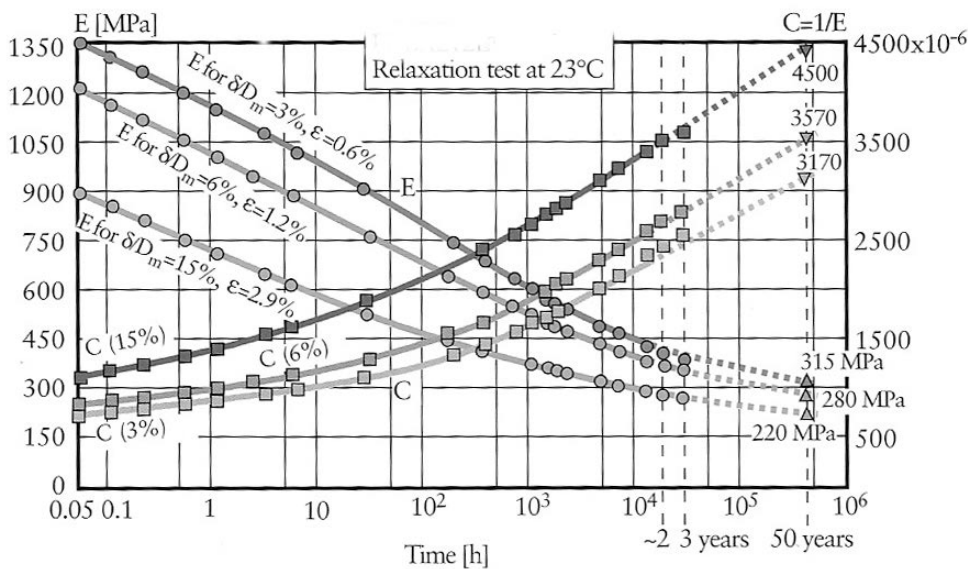
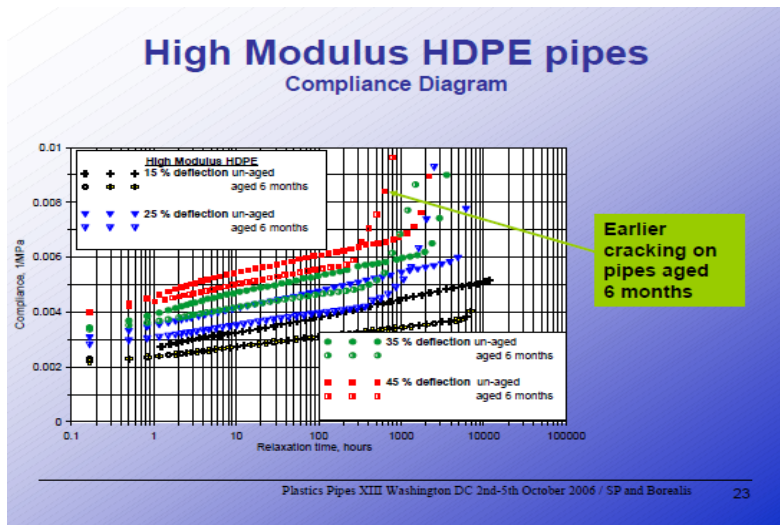


Figure 2.6.1 Relaxation curves from Janson [14]

In his studies, it has been found from these curves that the compliance curves (inverted value of the time dependent Relaxation modulus $1/E(t)$) follow a rectilinear line after a certain testing time and this straight line can then be extrapolated linearly in the $\ln C/\log t$ diagram. The linear course of the curves is explained as a result of physical ageing of the pipe material and similar principles are also experienced in creep tests under constant loading. The rectilinear part of the Compliance curve occurs relatively early in time and the onset of this linear behaviour is also depending on type of material and loading conditions; for PE the rectilinear part is often found before 1000 hours testing time and for PP normally this part is experienced at testing times around 1000 h and after. In the case of PE, the rectilinear course the Compliance curve occurs very early for highly strained material and after 10-100 h for less strained material [14]. This implies that the long-term E-values (50-100 years) can be found for most PE materials from a testing time of about 1000 h and longer.

The extrapolation of the data can reliably done over a period of 2 or 3 decades. Consequently, a testing time of 2000-4000 h would normally be considered sufficient for PE. For PP the rectilinear part starts normally at around 1000 h and would consequently require somewhat longer testing time. It is expected that for PP a minimum of 4000 h testing time, depending on material and loading conditions, would be sufficient for a relevant extrapolation procedure. Practically up to around one year testing time would be recommended for both PE and PP.

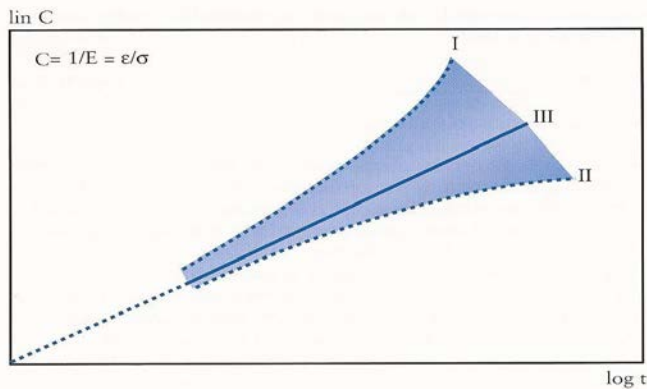


[23]. G. Bergström, S. Nilsson, K.Thörnblom, C.-G. Ek, H. Herbst, A. Stenström, *Plastics Pipes XIII*, Washington DC, 1-5 October 2006.

Figure 2.6.2 Relaxation curves [23]

Furthermore, from the curves in figure 2.6.1 it can also be seen that the relaxation modulus reduces very quickly to lower values in a short time, e.g. within 200 h the modulus has already been reduced to less than the half of the initial value. Pipes with poor quality can deviate from this linear relaxation behaviour as shown in figure 2.6.2. [23]. After a certain period, the relaxation behaviour deviates from the straight line due to poor material or pipe manufacturing practice or too heavy loading or a combination of all. In the example shown, based on a material not intended for use in non-pressure underground applications, cracks are formed and the Compliance curves are deviating from the expected behaviour of products fit for purpose. Consequently, in order to make reliable predictions of the long-term stability of the stability of the (pipe) material under constant strain conditions, a combination of long-term relaxation tests (and extrapolation of the Compliance $C=1/E(t)$) and corresponding visual inspections of potential cracks on the strained samples, are key ingredients.

For a good analysis and qualification of the measured relaxation curves, an explanation of the basic appearance of relaxation curves are also given by Janson [14]:



Janson defined schematically 3 possible basic shapes of the relaxation (Compliance) curves.

Figure 2.7 Principal curvatures of Compliance C versus log time by professor Janson, page 106. [14]

Curve I: C will reach infinity before time does, so E reaches zero in a limited time, so the loading is too high or the material is too weak. An example is given in figure 2.6.2 (red and blue dotted lines) where after a certain time cracking has started.

Curve II: C approaches a constant value within reasonable time. So the stress does not or not fully relax but the stress remains at a constant value and stress relaxation stops. The pipe material behaves elastic and a constant stress applies.

Curve III: C will approach infinity when the loading time does. This type of curve represents a stable relaxation behaviour of good pipe material and pipe construction where extrapolation at long term is possible. The stress does only relax to zero at infinity

It is clear that the relaxation curve must demonstrate a straight line as in Curve III where we can expect a stable pipe without damage or failure due to the loading condition until the calculated lifetime. In figure 2.6.1 this pipe behaviour has been illustrated for 3 %, 6 % and 15 % deflection. The straight lines of Compliance versus log time demonstrate a stable relaxation behaviour what allows a reliable extrapolation to long times.

In figure 2.6.2 it has been demonstrated that under certain conditions, the deflection becomes unstable and deviates from the straight line. This shows either bad quality or excessive loading in relation to the pipe properties, frequently accompanied by local cracking. (Curve 1 behaviour)

In this project, relaxation tests has been carried out according to the recommendations of Janson. [14]

2.2.7 Relaxation measurements

To demonstrate the long term behaviour under constant deflection, tests have been carried out during 13270 h by 15 % constant deflection at 23 °C and 45 °C. [Annex: 1,5]

The deflection of 15 % has been chosen as the extreme situation under which we would make clear that the pipes can perform satisfactory and consequently to demonstrate the safety in our

approach (EN476 allows a final deflection of 8 % whereby it also has been stated that incidental and local deflections up to 15 % will not cause a problem).

Three excavated pipe samples have been selected and compared with virgin pipes made of modern pipe grades used for non-pressure application.

The following samples have been selected:

Solid-wall pipes at 23 °C

200mm	PE virgin	SDR17		
200mm	PE excavated	SDR17	38 years old	Pipe code F1
110mm	PP-B virgin	SN6.3		
110mm	PP-B excavated	SN6.3	23 years old	Pipe code N1

Structured-wall pipes, (outside corrugated) at 23 °C and 45 °C (EN 13476-3, type B)

160mm	PP-B virgin	SN8		
160mm	PP-B excavated	SN8	21 years old	Pipe code N2

All tests are conducted with 2 specimen from each pipe sample. The tests have been carried out during 13270 h which gave a good opportunity to make reliable extrapolation possible (*tests at 45 °C only to 4000 h*). As it has been stated before, a maximum deflection in practice has been assumed of 8 % at 100 years. The relaxation tests have been carried out with 15 % deflection to show the safety in our approach and measuring extreme conditions. The 15 % deflection is based on the inner diameter.

The test results are given in figure 2.8. In figure 2.8.1 to 2.8.3 the measured relaxation moduli are given as a function of log time for all the tested samples. In figure 2.8.4 to 2.8.6 the same is done for the Compliance but in that case, the mean value of two samples are taken and the extrapolation until 100 years has been shown (dotted line). The extrapolation has been calculated from the last 12 measurements. In the graph, the line of linearity is shown by the coloured area. Also the reference curves [14] are copied into this graph as to compare with the measured lines. The correlation factor is also given and show a value > 0.99 which demonstrates a very good fit. Only one test at 45 °C deviates, the reason is not clear.

From the test results, it can be seen that in all cases, for both virgin and excavated pipes, the line for Compliance versus log time shows a straight line, compared to the reference is this a clear curve type III, which demonstrates a stable pipe material and pipe wall where a straight relaxation line to 100 years is expected.

Figure 2.8 Relaxation measurements on virgin and excavated pipes

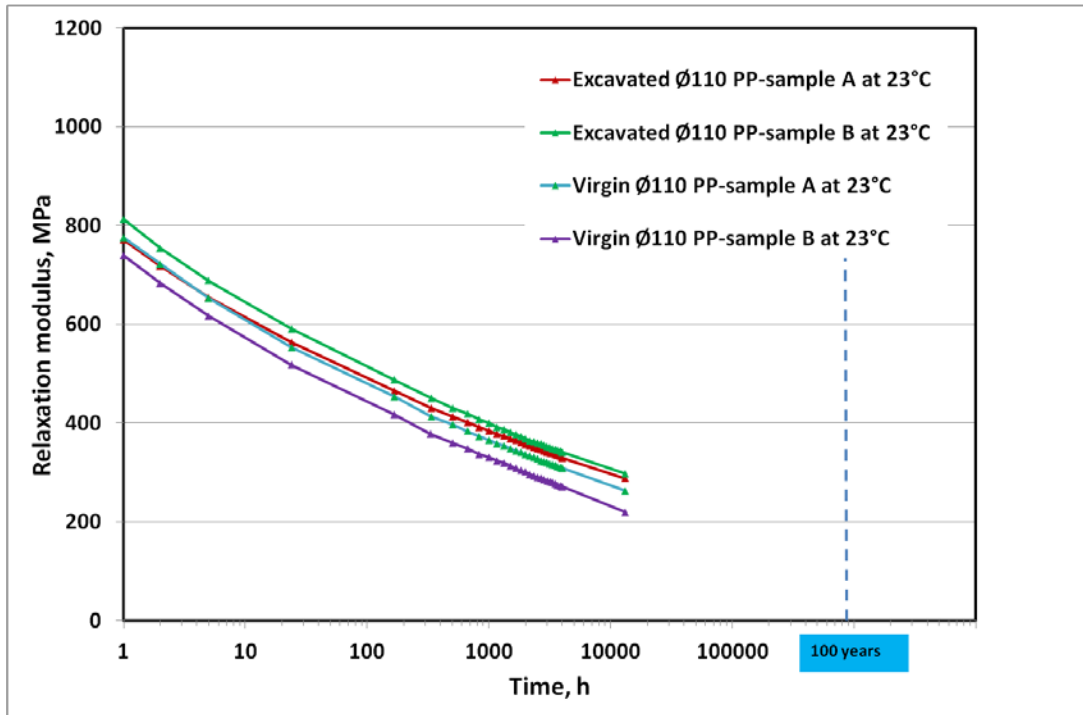


Figure 2.8.1 Relaxation modulus of 110mm PP solid wall pipe at 23 °C

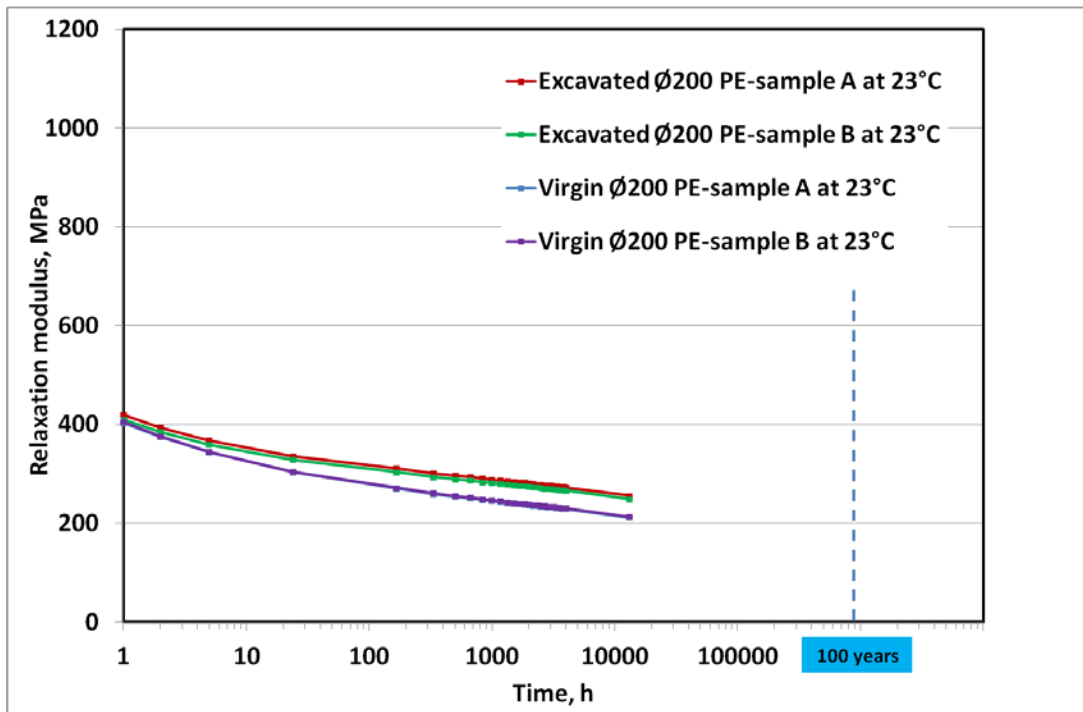


Figure 2.8.2 Relaxation modulus of 200mm PE solid wall at 23 °C

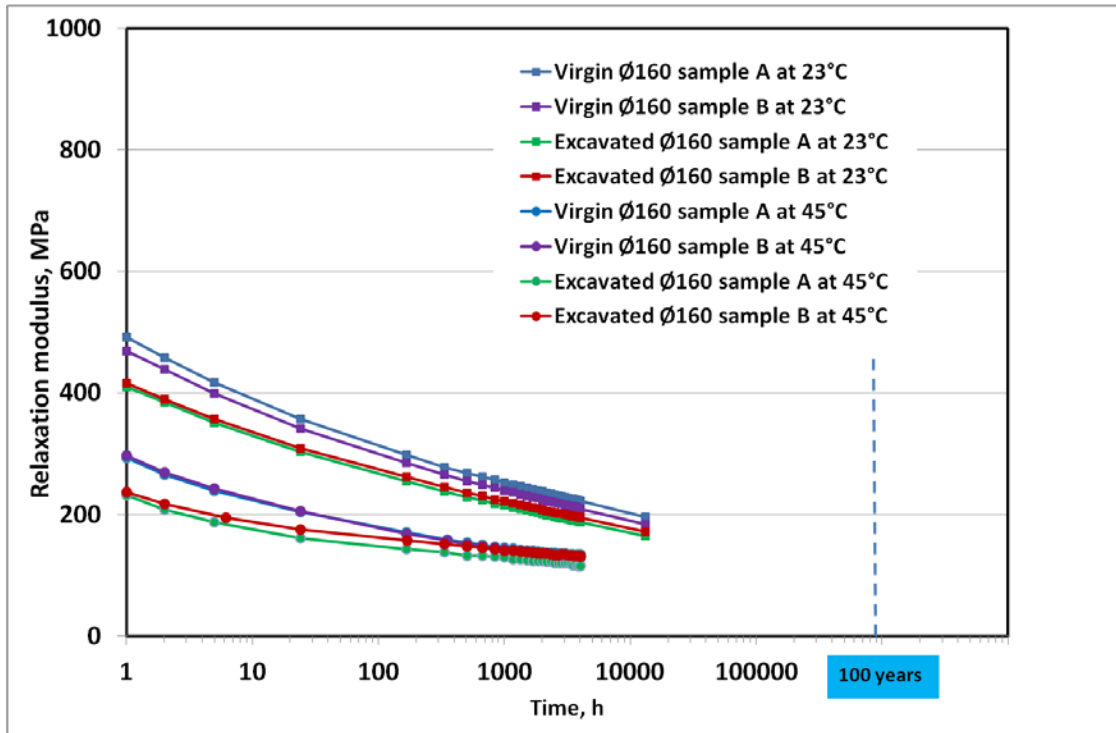


Figure 2.8.3 Relaxation modulus of 160mm PP structured-wall pipe at 23 °C and 45 °C

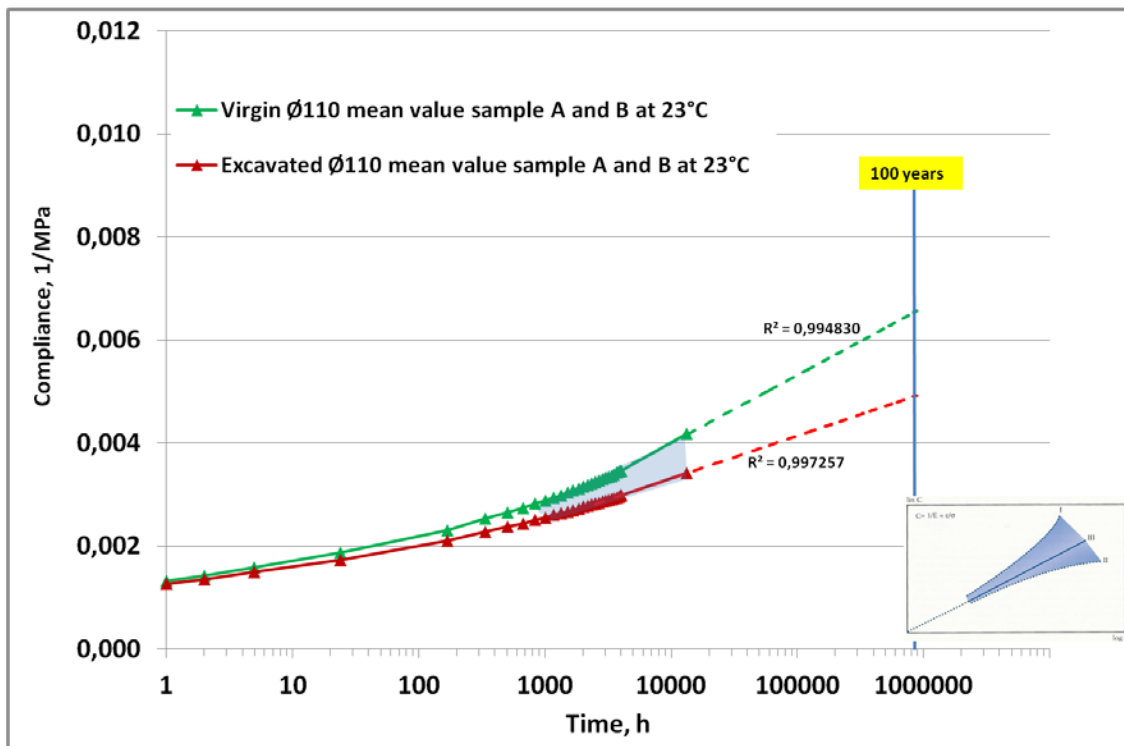


Figure 2.8.4 Compliance curves of 110mm PP solid wall pipe at 23 °C

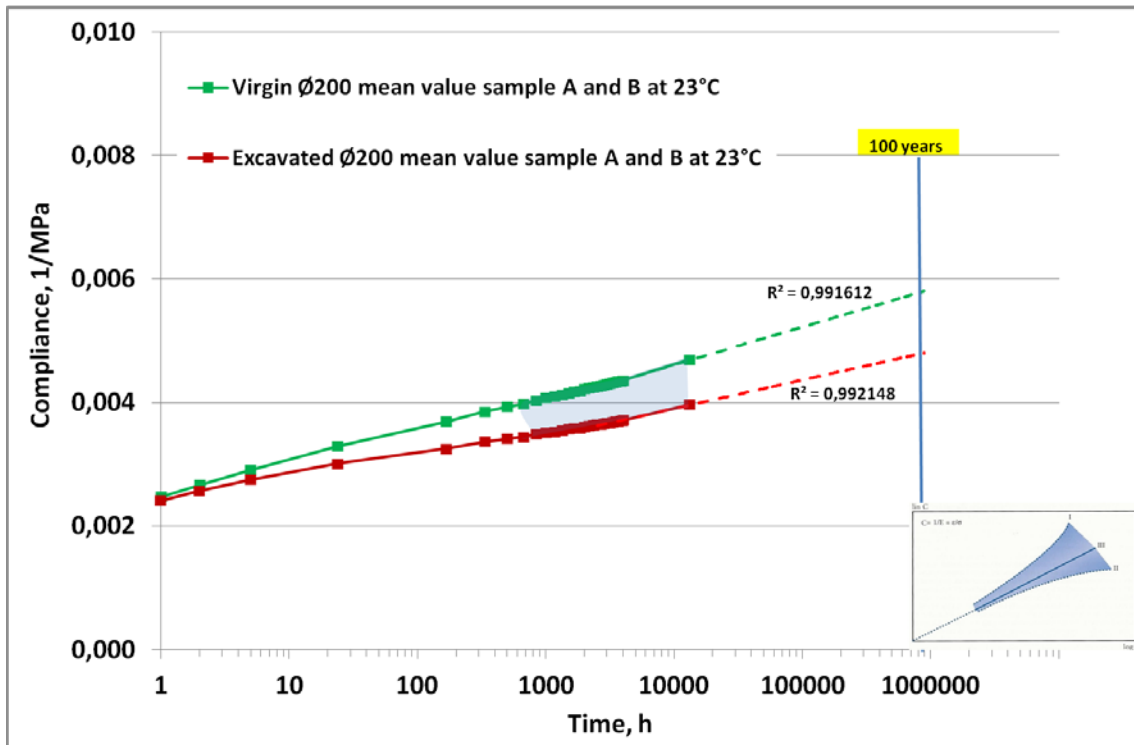


Figure 2.8.5 Compliance curves of 200mm PE solid wall pipe at 23 °C

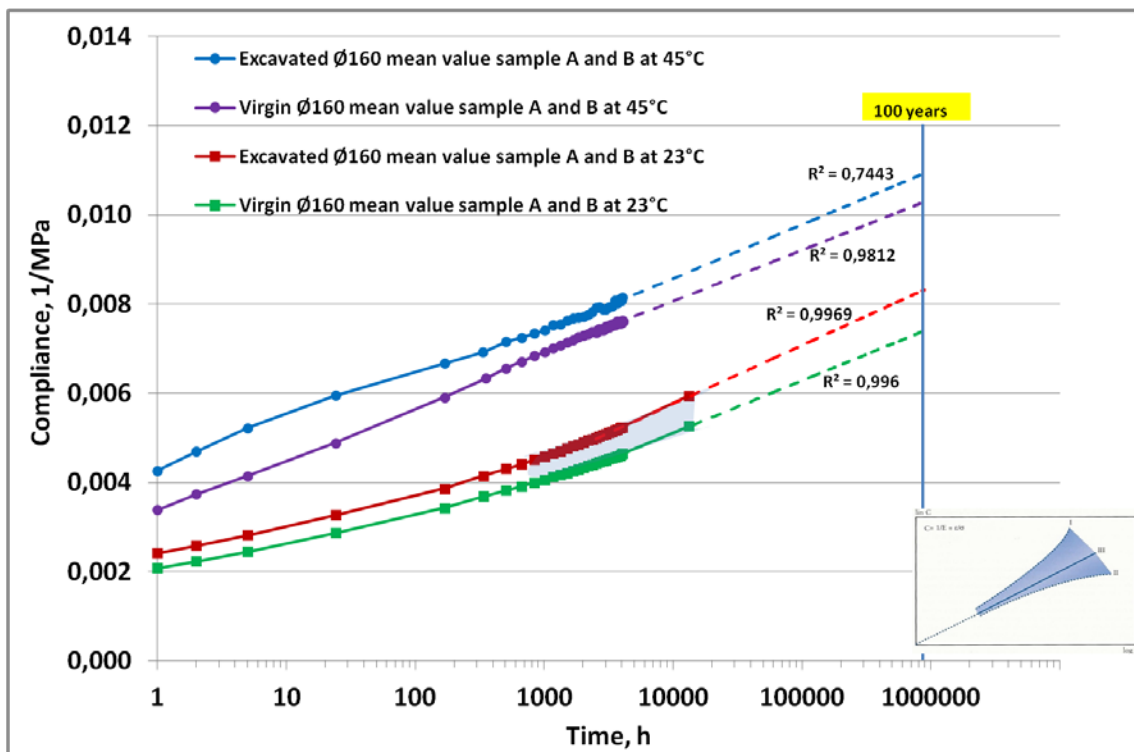


Figure 2.8.6 Compliance curves of 160mm PP structured-wall pipe at 23 °C and 45 °C

The 100 years extrapolated Compliance and Relaxation moduli are shown in the table 2.4. It is noted that the extrapolated relaxation values of solid wall pipes are lower for virgin pipes compared to excavated pipes. It should also be noted that the excavated pipes were already aged to quite some extent resulting in a higher stiffness. This however is not the case for the structured-wall pipe samples, where the virgin pipes show the higher relaxation value. For the time being, there is no explanation for this.

Table 2.4 Relaxation moduli (MPa) and Compliance values (1/MPa) extrapolated to 100 years, based on relaxation measurements up to 13270 h

Tested samples	Relaxation modulus [MPa]	Correlation Factor R *)	Compliance [1/MPa]
Ø 200mm, Excavated SW PE pipe code F1, at 23 °C	208	0.996	0.0048
Ø 200mm, Virgin SW PE pipe, at 23 °C	172	0.996	0.0058
Ø 110mm, Excavated SW PP-B pipe code N1, at 23 °C	203	0.999	0.0049
Ø 110mm, Virgin SW PP pipe, at 23 °C	153	0.997	0.0066
Ø 160mm, Excavated SWP PP-B pipe code N2, at 23 °C	120	0.998	0.0083
Ø 160mm, Virgin SWP PP-B pipe, at 23 °C	135	0.998	0.0074
Ø 160mm, Excavated SWP PP-B pipe code N1, at 45 °C	92	0.863	0.0109
Ø 160mm, Virgin SWP PP-B pipe, at 45 °C	97	0.991	0.0103

(SW = Solid-wall pipe, mono-layer; SWP = Structured-Wall Pipe type B acc. to EN13476-3)

*) The correlation factor R has been calculated from the last 12 measurements. A value of $R > 0,99$ demonstrates a very good correlation and straightness of the curves

***) The values above are the mean values of 2 samples

2.2.8 Calculated strains in the deflected pipe and the remaining stresses

Based on the relaxation test results reported above, the strains and stresses that occur in practice can now be estimated and analysed. To repeat, the 15 % deflection in the tests are chosen to demonstrate the behaviour under extreme conditions. This extremity also follows from the previously mentioned Teppfa design graph, where it can be read that for a SN8 pipe, the initial deflection for "none" compaction of the backfill (the worst condition) is 6 % and the final deflection at long term is then 10 %. We even tested and calculated at 50 % higher deflection level. Based on the relaxation curves with this deflection of 15 % the remaining stresses could be calculated according to the formulae in clause 2.2.4. Here the calculated stresses are the stresses in the outer fibre. For structured-wall pipes it is the top of the profiled outer wall.

Table 2.5 Stresses and strains of SN8 pipes after relaxation by 15% deflection

110mm PP solid wall pipe SN8 at 23 °C

	15 % deflection		1.55 % strain		
	1 h	24 h	4000 h	13270 h	100 y
Relax. Mod. MPa	774	556	313	267	190
Stress MPa	12.03	8.64	4.87	4.15	2.95

160mm PP structured-wall pipe SN8 at 23 °C

	15 % deflection		3.39 % strain		
	1 h	24 h	4000 h	13270 h	100 y
Relax. Mod. MPa	447	328	204	179	135
Stress MPa	15.15	11.11	6.91	6.06	4.57

200mm PE solid wall pipe SN8 at 23 °C

	15 % deflection		2.16 % strain		
	1 h	24 h	4000 h	13270 h	100 y
Relax. Mod. MPa	409	318	250	232	201
Stress MPa	8.83	6.87	5.40	5.01	4.34

The same has been done for structured wall pipes at a temperature of 45 °C

160mm PP structured-wall pipe SN8, with 15 % deflection at 45 °C, strain 3.39 %

	1 h	24 h	4000 h	100 y
Relax. Mod. MPa	265	200	140	97
Stress MPa	8.98	6.78	4.74	3.29

A first remark can be made that also with 15 % deflection the maximum strains in structured-wall pipes are still significantly lower than the suggested maximum strainability of 5 %. The remaining stresses at 23 °C, in particular for structured-wall pipe, are still rather high.

It can be seen that for all pipes, the initial stresses at 15 % deflection are indeed quite high but these relax very strongly within a short time period. From the relaxation curves of the structured-wall pipes 160mm PP-B, it has been seen that after 1 h a stress of 15.2 MPa has been measured, but after 1000 h relaxation time, the stress is already lower than the allowable stress of 7.9 MPa (see clause 2.2.1) It can also be noted that during this "high stress" period in the relaxation tests, no failure or pipe instability has been observed and the curve remained straight from this moment on.

The test results at 45 °C show that the relaxation process accelerated and resulted in much lower stresses, also lower than the critical value at 100 years. In clause 3, it has been demonstrated that in practise the operating temperature is much lower than 45 °C. This means that the temperature limits as defined in the standards are not a threat for the pipe material because it speeds up the relaxation and reduces the stresses. In that situation the functionality of the whole piping system is more important.

It may also be noted that the straight curves until 4000 h demonstrate no tendency of failure, so with the relaxation tests in combination with the corresponding visual/microscopy analysis for identification of potential cracks or damages, it has been demonstrated that the initially acting (high) stresses will not cause instability or tendency to failure.

It has to be noted that the PE pipe with the same stiffness class SN8 at 23 °C shows a higher strain at the same deflection level due to the thicker wall (SDR21 for PE compared to SDR29 for PP-B pipe). And where for PE the initial stress is lower (due to lower initial E-modulus) than for PP-B, the final extrapolated stress value at 100 years is higher for PE (3.95 MPa) than for PP-B (2.60 MPa)

Note: In the relaxation tests a constant deflection is used, in this case 15 %. Related to practice, the calculated stresses are quite at the pessimistic side.

In practice the loading of the pipes is much more complex. When pipes are installed under the condition of good workmanship, the deflection of e.g. a SN4 pipe directly after installation is no more than 3.5 % and within about 2 years of soil settlement, a final deflection can be expected of 5.5 %.(see clause 2.2.3) But during this 2 years period of increasing deflection, also the relaxation of the stress will take place. So the real acting stress in the pipe is always lower than the calculated one.

When in practice incidentally a deflection of 15 % is reached at long term (100 years) it can be assumed that the initial deflection will be about 10 %. Consequently, in practice the resulting stresses in the pipe will never reach the high levels with which we have tested and calculated.

When the sewer is in operation, also the temperature rises to 30 °C or more, and the stresses reduce again.

This means that in the solid wall pipe the stresses will remain far below the allowable stress. Also in case of structured-wall pipes, the stresses can be estimated as not critical. It remains important to make sure that at initial loading (at installation), the stresses will not be build up too quickly and possibly causing initial yielding or cracks. For that reason a 30 % Ring Flexibility tests at short term in combination with a long term relaxation test (at least 4000 h), where no cracking and discontinuous relaxation behaviour have been observed, provide a maximum assurance that the pipes can perform for more than 100 years without failure.

Based on these test results, also an analysis has been made for the case of the more realistic limit of 8% deflection at long term, and as allowed in CEN/TR 1046.

Here it has to be taken into account that the relaxation moduli for lower deflection are higher, see annex 2. For our calculations at 8% deflection the relaxation moduli are estimated at 30% higher than those for 15% deflection.

Table 2.6 Stresses and strains of SN8 pipes after relaxation by 8% deflection

110mm PP solid-wall pipe SN8 at 23 °C

	8 % deflection		0.83 % strain		
	1 h	24 h	4000 h	13270 h	100 y
Relax. Mod. MPa	1006	723	407	347	247
Stress MPa	8.34	5.99	3.37	2.88	2.05

160mm PP structured-wall pipe SN8 at 23 °C

	8 % deflection		1.81 % strain		
	1 h	24 h	4000 h	13270 h	100 y
Relax. Mod. MPa	581	426	265	233	176
Stress MPa	10.50	7.71	4.79	4.21	3.17

200mm PE solid-wall pipe SN8 at 23 °C

	8 % deflection		1.15 % strain		
	1 h	24 h	4000 h	13270 h	100 y
Relax. Mod. MPa	532	413	325	302	261
Stress MPa	6.13	4.76	3.74	3.47	3.01

160mm PP structured-wall pipe SN8, with 8 % deflection at 45 °C

SWP SN8	1 h	24 h	4000 h	100 y
Relax. Mod. MPa	345	260	182	126
Stress MPa	6.23	4.70	3.29	2.28

Here it can be seen that with a deflection of 8 % after 24 h operation, in all test samples the relaxation stresses are already lower than the previously mentioned allowable stress level of 8.0 resp. 8.4 (see table 2.3). For structured-wall pipes the stress level is a little higher than for solid wall pipes but not critical, and in the case of the required maximum temperature of 45 °C, the stress become much lower than the allowable stress of 4.0 MPa. In this example, only calculation results are shown of 160 mm structured-wall pipes type B acc. to EN13476-3.[6]

The maximum strain values of all other diameters and other types of profiles have been verified as well and in practice these differ only very little so that the shown figures are quite representative.

In the case of PE pipes, solid wall or structured-wall pipes, the calculations show lower initial figures as for PP-B pipe but higher figures at long term but these will never come at a critical value due to higher allowable stresses. It also may be clear that for SN4 and SN2, the stresses will also be much lower, so that these are also safe.

Note: With a final deflection of 8 %, an initial deflection is normally not higher than 6 %. In that case, the maximum initial stresses are far below the yield stress, even for structured wall pipes. For that reason, requiring a maximum of 8 % long term deflection is a safe approach

2.2.9 Interpretation of strain and stress calculations

EN476 [1] requires that pipes shall be suitable for a continuous water discharge temperatures for sewers diameters ≤ 200mm of 45 °C (mainly drainage lines) and for diameters > 200mm is this 35 °C (mainly sewer mains).

It is well known that in practise, a pipe is not constantly loaded at these maximum temperatures. From the TGM study (see clause 3) it has been learned that the maximum temperature is never higher than 30 °C and normally varies between 15 and 20 °C.

This all means that with a limited long term deflection of 8 %, the stresses will not exceed a critical value. Even in extreme situation where the deflection increases to 15 %, either calculated with a temperature of 45 °C and the relaxation modulus at that temperature, or calculated with a temperature of 30 °C and the relaxation modulus at that temperature will not exceed the critical values.

It is also good to realise that the calculated long term strength of 4.0 MPa at 45 °C (see clause 2.2.1 of this report) for PP-B is based on a continuous stress at this temperature. As seen in the TGM report that in practise the temperatures are normally below 20 °C, in that case the allowable (constant) stress at 100 years is 8.4 MPa and in cases of peaks until 30 °C, the allowable stress is still 7.0 MPa, see table 2.7.

Table 2.7 PP-B Structured-Wall Pipes, allowable and calculated stresses at 100 years, based on SP study [Annex,1]

Temperature	Allowable stress	Stresses in MPa at deflection of		Relaxation Modulus *)
		8 %	15 %	
20 °C	8.4	3.2	4.6	176/135
30 °C	7.0	2.6	4.1	**)
45 °C	4.0	2.3	3.3	126/97

*) At 8 % deflection, the modulus is assumed to be 30 % higher than for 15 % deflection.

***) Stress values at 30 °C are estimated by interpolation

This table demonstrates that when we assume either a constant stress at 23 °C or at 45 °C and calculating with the relaxation modulus for that temperature, in both cases the allowable stress

will not be exceeded. Also in case of the more realistic temperature of 30 °C is taken, no critical limit will be reached. However, it has to be noted that this is a comparison made including stress levels in a structured-wall pipe estimated to be reached at 100 years. Higher stresses are naturally experienced at shorter times and are discussed further below.

It should also be emphasized that it is not realistic to compare the allowable stress at 45 °C versus the calculated stresses at 23 °C.

Nevertheless, the initial stresses induced by deflections up to 15 % can be rather high and can be a reason for failure at short term.

By securing

a) high quality resins intended for underground sewer applications, i.e. fulfilling requirements according to Table 1.1,

b) reliable performance of stress relaxation tests according to Janson [14] at 15 % and testing time minimum 4000 h also enabling stresses to relax to levels below max allowable stresses

c) complemented with microscopic analysis of strained pipe samples at the end of the Janson test to secure no cracks or damages

the statement by Janson [14] is considered to be fully supported; when failure does not occur at short term (e.g. 4000 h), it is very unlikely that it will ever occur.

When the maximum strain should be the determining criteria, it can be concluded that in the outer fibre of structured wall pipes, the strain (3.4%) will remain below the critical 5%

These exercises demonstrate that with the recommended maximum allowable deflection of 8%, we are at the very safe side and even when incidentally a deflection of 15 % should occur, the remaining stresses are still not critical and it cannot be expected it will cause pipe failure within the whole predicted lifetime.

2.3 Stress concentrations, finite elements analysis, visual inspection, wall design

Independent from the type of material, it has been realised that in structured-wall pipes, stress concentrations can be seen at some critical points in the wall construction, which could exceed the calculated values.

For that reason, to identify positions of critical stress concentrations, a finite elements analysis has been carried out on a PP structured-wall pipe design i.e. a 300mm, double wall construction (outside corrugated) at 6 % and 15 % deflection. [Annex: 2]

It has been seen that at particular positions, point A and B in the corrugation, higher stresses can be determined. Therefore, it is important to analyse whether in those cases yielding will occur or crack initiation will be started. This is also a procedure which is included in the requirements for the 100 years lifetime expectancy, see Table 1.1.

Visual inspections of the samples showed that no stress whitening did take place, neither any sign of crack initiation.

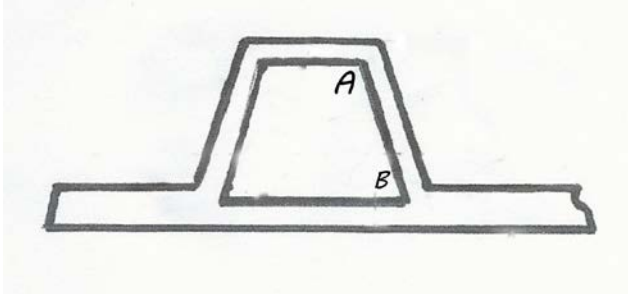


Figure 2.8, Example of an analyzed wall construction type B acc. to EN13476-3

It also has to be emphasized that analysis of the relaxation curves has not shown any discontinuity in the relaxation. Cracking should result in a deviation of the straight relaxation curve what did not occur. occur i.e. supporting the results from the visual inspection.

On the other hand, a short term 30 % Ring flexibility test and impact tests as defined in the product standards are certainly capable in selecting poor pipe design and materials.

Nevertheless, it remains a critical aspect and by designing a structured-wall pipe, these possible stress concentrations should be considered carefully and reduced as far as possible. The principles outlined for identifying positions in the structured-wall pipe design with higher stresses are also important when examining pipes by microscopy analysis for cracks and damages at the end of the Janson test, see Table 1.1.

2.4 Final remarks

2.4.1 In clause 2 of this report, maximum allowable stresses are calculated by which a 100 years service-lifetime at 45 °C can be assured. Under these most extreme conditions, PP-B can at 45 °C withstand a stress of 4.0 MPa and for PE80 it is 5.5 MPa. In practice, the real temperatures are not higher than 30 °C and the allowable stresses are also higher. This means that in practice there is a firm safety factor compared to our assumptions.

2.4.2 The outcome of this study is that with a maximum allowable pipe deflection of 8 % , a 100 years service-lifetime can be expected. In the previously mentioned Teppfa study "Buried Pipes" [15], this limit of the deflection is well proven as being representative for practice and is also a requirement in the relevant CEN standards.

2.4.3 Based on the relaxation tests, the stresses (after relaxation) are calculated at the outer fibre of the pipe profile. In spite of the relatively high stresses that can occur at the beginning of the loading by 8 % deflection, due to the relaxation these stresses are for structured-wall pipes of both PP and PE normally reduced below the allowable stress within 24 h. By 15 % deflection, the stresses are reduced below the allowable stress within 1000 h. For PE pipes this is already the case within 1 h. Based on the extrapolated relaxation modulus at 100 years. the remaining stresses for an allowable pipe deflection of 8 % or 15 % are far below the critical stress levels.

2.4.4 In this study relaxation tests are executed at 15 % deflection. Short term and long term stresses are calculated under a constant deflection of 15 % where the remaining stresses at long term are close to the limits. The strains in the pipe wall remain below the critical limit of 5 %.

2.4.5 Relaxation measurements carried out at PP-B solid-wall pipes, PP-B structured-wall pipes and PE solid wall pipes, virgin and excavated pipe samples, with a constant deflection of 15 % during 13270 h (1.5 year) do not show any discontinuity in the compliance curve and no visible cracks, so that extrapolation of these curves to 100 years are considered reliable. This means a safety factor of approximately 2 compared to the allowed maximum deflection of 8 %.

2.4.6 The initial stresses induced by pipe deflections up to 8 % or 15 % are expected to be high and can be a reason for failure at short term. By securing **a)** high quality resins intended for underground sewer applications, i.e. fulfilling requirements according to Table 1, **b)** reliable performance of stress relaxation tests according to Janson [14] at 15 % and testing time minimum 4000 h also enabling stresses to relax to levels below max allowable stresses and **c)** complemented with microscopic analysis of strained pipe samples at the end of the Janson test to secure no cracks or damages, the statement by Janson [14] is considered to be fully supported; when failure does not occur at short term (e.g. 4000 h), it is very unlikely that it will ever occur. Consequently a failure during 100 years operation is not expected.

2.4.7 In a structured-wall pipe type B acc. to EN13476-3 [6], stress concentrations have been allocated by finite elements analysis. These observations emphasize that a maximum of 8 % deflection at long term should be required. In order to assure that the wall structure under these conditions is stable and strong enough to withstand external loading, also a 30 % ring flexibility test and the impact test in the product standards is of crucial importance to provide proof of the stability of the wall structure at short term. Also with the relaxation tests on structured-wall pipes as conducted in this study and complemented with visual inspection of the pipes versus cracks and damages, a stable and continuous relaxation process can be demonstrated. Also this test is considered as important to demonstrate the reliability and stability of the wall construction at long term. These tests are also important to prove the good quality of the welding line between the two layers in type B pipes.

2.4.8 The relaxation measurements at 45 °C show also a straight line. In case the temperature of a sewer line is continuously 45 °C, the pipe will well perform at long term whereby the stresses relax to lower levels and consequently the risks will reduce.

3. Effect of sewer water

3.1 Introduction

The stage III failure modes are the so called end-of life stage where the stabilizer has been consumed completely and the material loses its integrity. In order to determine if stabilizer consumption is effected by the water quality, in our case sewer water, it should be part of the investigation.

It is known that pure chemicals or in high concentrations effect the lifetime of polyolefins. The effect is depending of the type of chemical and the type of material on which it is acting, i.e. in contradiction to concrete, polyolefins have an increased lifetime when in certain environments like acid groundwater (externally) or hydrogen sulphide/sulphuric acid (internally) [1]

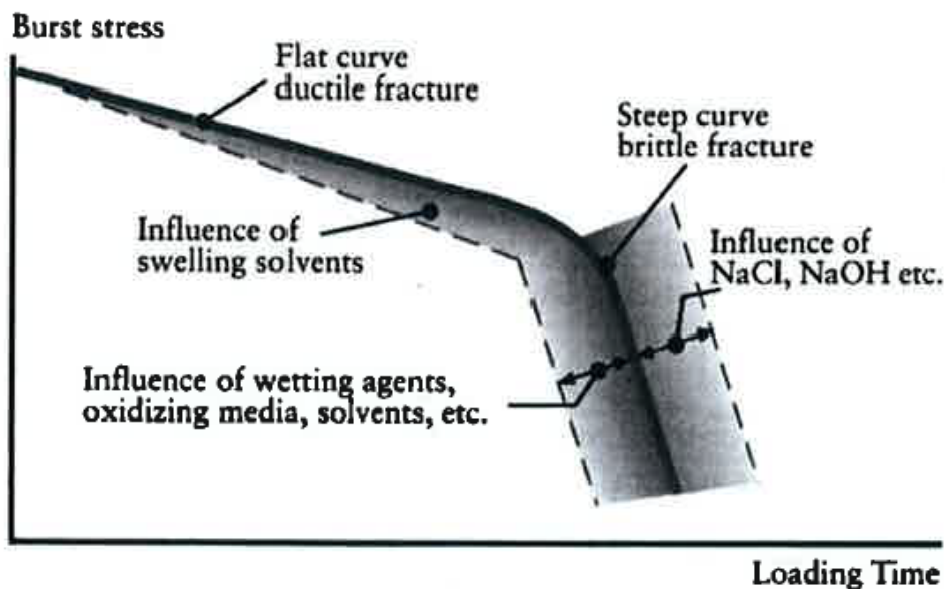


Figure 3.1. The influence of different mediums on the stress/time curve's position for PE pipes subjected to intern hydrostatic pressure [17]

However in most laboratory investigations high concentrations are used which are normally not present in sewer water. A better insight of the composition and concentration of the sewer water might be of help for estimating the risk of earlier failures.

3.2 Approach

To confirm the relatively low concentrations in sewer water, an intensive literature study has been performed by TGM at the request of the Teppfa working group. This is to obtain a better picture of the composition of sewer water. (Annex, 4)

In this work the composition of 15 purification facilities in Austria have been investigated to determine the composition of the water in comparison with the valid country guidelines. The incoming water is coming from 3 different sources and can vary from facility to facility. The

rough composition is 10 % rainwater, 50 – 70 % sewer water and 20-40 % mixed (sewer and rain)water.



Figure 3.2. Typical composition of the sewer water in department "Oberösterreich" in Austria (9 % rainwater, 50 % sewer water and 41 % mixed water) [Annex, 4].

The composition of more than 100 chemicals have been analyzed towards its content.

Abbild 5: Inhaltstoffe [$\mu\text{g}/\text{l}$] der beprobten Kläranlagenzulaufe (ARA 1 bis ARA 15)

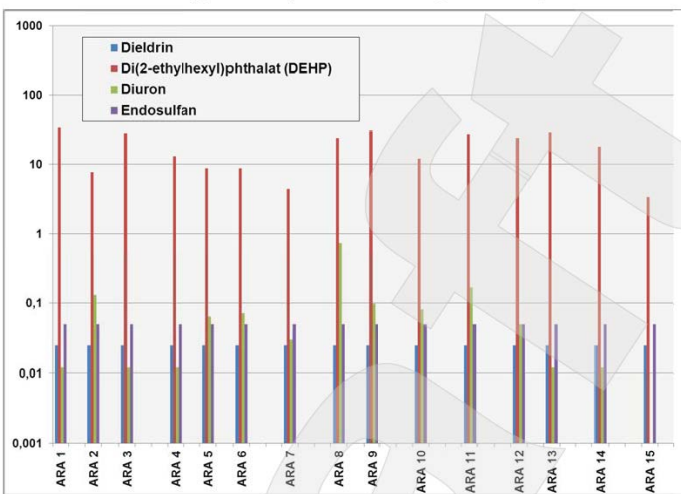


Figure 3.3 Typical figure of content of four chemicals present in the 15 investigated cleaning facilities called ARA's.

By analyzing the chemical resistance tables available for PE and PP in combination with the content of sewer water from the above study, an estimation is made on the expected risk for shorter lifetime.

3.3 Results

TGM found that all investigated chemicals are within the local valid guidelines. This already indicates that no problems should be present due to sewer water attack otherwise claims from the market would be addressed by Pipe producers. So far no claims are known [17] which are

related to the attack of PE and PP pipes by sewer water. Furthermore the origin of some chemicals could directly be related to the industrial sewer lines on the networks.

Looking at the materials with the highest concentrations we can find 4 types:

- Benzene with concentration of approximately 1 mg/ml
- AOX (absorbable organic chlorine carbons) with concentration of 1- 10 mg/l
- Fluoride with concentration of 10 – 100 mg/l
- LAS (linear alcybenzene sulfonates, anionic surface active agents, soaps, detergents) with concentration of 1-10 mg/l.

From these the benzene (aromatics in general) and LAS are based on chemical resistance data expected to be most aggressive to PE and PP.

Fluorides are inorganic and not a problem. And the AOX are so low in concentration that no effect is expected.

Benzene and aromatics.

The solubility of aromatics is normally limited. Depending on type is 200 – 1800 mg/liter. With respect to permeability KIWA conducted an intensive investigation and advice not to use pipes above 25 % of the solubility. The values found in this investigation are much lower. Tests have shown no effect of saturated mixture of aromatic on hydrostatic test results. Toluene saturated tests at 80 °C, Hexane naphthalene and toluene tested at 20 °C. Conclusion from this is that the contents found in the sewer water are not expected to be a problem.

LAS (surface active agents, soaps and detergent).

Also for this group of detergents the concentration level found, are very low. However it is known how to accelerate brittle fractures; LAS are in use to reduce testing times significantly in much higher concentrations. Any effect of the low concentrations found is unknown. So far we are not aware of any claims which are related to the attack of PE and PP pipes by soaps in the sewer water [17].

3.4 Conclusion for possible effect of sewer water

From the investigations conducted no problems are expected due to accelerated aging of the pipes by sewer water due to the low concentrations found. Even if the concentrations are temporary higher (short shock loads) at connections closer to the house no effect would be expected.

Remark

In case the European guidelines for contents in surface water are changed, the standardization committees should take care about the effects on new and existing pipes.

3.5 Temperature of sewer water system

3.5.1 Introduction

In the concept of the study the lifetime of 100 years is based on a continuous water discharge temperature of 45 °C as described in EN 476 [1] for gravity sewer with diameter ≤ DN 200 outside buildings. (For diameters > DN200 the maximum temperature shall be 35 °C). To be able to get an idea if this value is over-specified a better picture of actual temperatures is needed.

3.5.2 Approach

To check the sewer water temperature indicated as reference in the standard [1], a literature study has been performed by TGM on request of the Teppfa working group. Temperature data has been collected at four different objects. (Table 3.1) The temperature has been monitored during 1 working day.

3.5.3 Results

TGM found in literature that the average temperature over the day was approx. 25 °C , in this analysis the temperature did not exceed 30 °C.

Table 3.1 Indicated temperatures in TGM investigation

	Average [°C]	Max [°C]	Min [°C]	Remark
Student house 1	25	27	19	Lower in night
Student house 2	25	27	23	Lower in night
Hotel	22	28	17	Peak from 6-9 hour a.m.
Hospital	26	27	25	Constant day/night

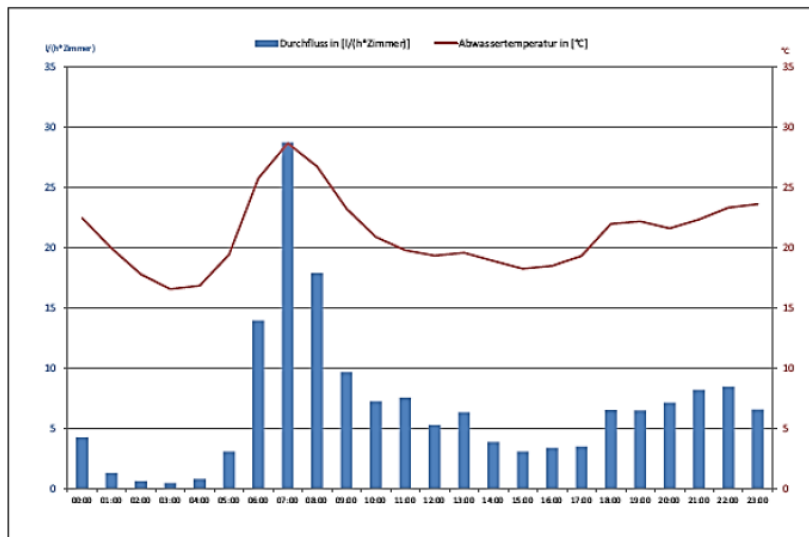


Figure 3.4 Example of temperature profile (red) in relation to drinking water use (blue) over 24 hour in a hotel [Annex, 4].

The found temperature ranges are comparable with the information from a report of Berliner networks [Annex, 4].

Tabel 3.2 Indicated temperatures in Berlin network

Heat sources		
Range		Temperature [°C]
Sewer water	In buildings (houses)	+15 to + 25
	In pipe systems(waste water treatment plants)	+10 to +15
	Industrial sewer water	Up to 60

3.5.4 Conclusion for temperatures in sewer systems

From the investigations carried out we see that the data from Berlin is similar to that from Austria. Further it is found that in practice the temperatures are lower (15 – 20 °C) than those indicated in the standard 45 °C (or 35 °C respectively) indicating that we have a added safety margin.

Remark

For industrial sewer water higher temperatures may be present and therefore other pipe specifications may be applied.

4. Excavation projects

4.1 Excavated sewer pipes, with solid wall and structured wall

The quality and the prediction of the remaining lifetime of pipes that have already been in service in a sewer network for long periods are very important to launch a statement for a predicted lifetime of more than 100 years. It is therefore important to understand how pipes deteriorate in use as well as what remaining life time we can predict for the pipes already in use. To determine these aspects, different types of pipes were excavated at five different locations. On the excavated pipes several tests have been performed which are partly required by the relevant standards, additional analytical analysis has been done to provide information related to the used material and stabilisation.

4.2 General information of the excavation projects

In this project, pipes at 5 locations have been excavated for testing.

These are

Pipe F1	Finland, Vaasa	PE63, 200mm solid wall SDR17
Pipe G1,	Germany, Gottingen	PE80, 355mm SDR17.6 solid wall multi-layer *)
Pipe G2	Germany, Gottingen	PE80, 280mm SDR 17.6 solid wall multi-layer *)
Pipe G3	Germany, Gottingen	PE80, 280mm SDR 17.6 solid wall
Pipe N1	Norway, Vanvikan	PP-B, 110mm solid wall pipe class S14
Pipe N2	Norway, Surnadal	PP-B, 160mm structured-wall pipe SN8 **)
Pipe D1	Denmark, Skyve	PP-B, 200mm structured-wall pipe SN8 **)

*) *Pipe type A according to EN13476-2 [19]*

***) *Pipe type B according to EN13476-3 [6]*

4.2.1 PE solid wall sewer pipes from Finland, pipe code F1

Pipe code	F1
Location:	Vaasa
Soil type:	Clay, backfill with sand
Deflection after recovery:	2 %
System:	Municipal sewer water
Installation depth:	2.0 meters, ground water table 1.6m from soil level
Pipe material	PE (first generation)
Pipe type:	DN/OD 200mm solid wall, SDR17, PN6
Pipe installed in	1974 (38 years in operation)

The sewer pipes were installed in 1974 in Vaasa, Finland and have been in service for about 38 years. The pipes were produced from 1st generation HDPE pipe material, which was the common PE pipe material until 1978. Such 1st generation HDPE pipe resins were homopolymers and classified as PE63 according to an extrapolated 50 years pressure resistance at

20 °C / 6.3 MPa. Longitudinal scratches were present on the external surface of the pipe used for tests, which may have been caused by the excavation (see figure 4.4).

The deposits at the internal surfaces indicate that the pipes were only partially flooded by waste water (see figure 4.5). The non-flooded area of the pipe was estimated as 60 % and the flooded area about 40 % of the total cross-sectional area.



Figure 4.1
Location of the excavation site in
Vaasa Finland, Pipe F1



Figure 4.2
Excavation work, Pipe F1



Figure 4.3 Excavated pipes, PE 200mm in Finland, Pipe F1



Figure 4.4 Scratches at the external surface, pipe F1



Figure 4.5 Deposits from waste water at the internal pipe surface marking the flooded area of the sewer pipe, F1

4.2.2 PE Solid wall sewer pipes from Germany, Pipe codes G1, G2 and G3

Location:	Göttingen
Pipe material:	PE80
Pipe codes:	G1: DN300, SDR17.6, Dimension 355x20.1mm Multi-layer: inner layer naturel, outer layer black G2: DN250, SDR17.6, Dimension 280x15.9mm PE80, 280mm SDR 17.6 solid wall multi-layer G3: DN250, SDR 17.6, Dimension 280x15.9mm, mono-layer
Pipes installed in	1994-1996 (16-18 years in operation)

The excavated pipes, supplied from Stadtwerke Göttingen, Germany were produced and installed in the years 1994 till 1996 in Göttingen and have since then been in service for about 16-18 years. Three of the sewer pipes are coextruded pipes with an internal layer of natural HDPE resin and an outer layer of black pigmented material (see figure 4.6). The remaining two pipes are monolayer pipes made from black HDPE marked with brown stripes (see figure 4.7). Based on the markings on the pipes PE 80 pipe resins were used. One pipe sample has a sliding socket, all others only cut ends.



Figure 4.6 Coextruded pipes with internal layer of natural PE, Pipe G1



Figure 4.7 Black pipes with brown stripes, pipe G3

Table 4.1 Pipes from Germany, dimensions

Pipe Nr	Construction	DN	SDR	Dimension (mm)	Pipe Code
1, 2	Coextruded Pipe: Inner layer: natural PE Outer layer: black PE	300	17.6	355x20.1	G1
3	Coextruded Pipe Inner layer: natural PE Outer layer: black PE	250	17.6	280x15.9	G2
4, 5	Monolayer Pipe: Black PE	250	17.6	280x15.9	G3

The pipe samples with a length of 1 meter were printed with the following text:

1. Coextrudiertes schwarzes Rohr mit heller Innenschicht, D280, SDR17.6
Signature: Egeplast – 45 – SL PE-
HD005 COEX DIN8044/75 PE80 SDR17.6 DIN19537 R4 DN250 280x15.9
Handbeschriftung: Göttinger Königsalle Auslauf 52250, 21.8.2012
mit Friafit Schachteinbindung
2. Coextrudiertes schwarzes Rohr mit heller Innenschicht, D355, SDR17.6
Signature: Egeplast – 45 – SL PE-
D005 COEX DIN8044/75 PE80 SDR17.6 DIN19537 R4 DN300 355x20.1 129
m 21.8.00
Handbeschriftung: Auslauf 12016, 28.8.2012 mit Friafit Schachteinbindung
3. Coextrudiertes schwarzes Rohr mit heller Innenschicht, D355, SDR17,6
Signature: Egeplast – 45 – SL PE-
D005 COEX DIN8044/75 PE80 SDR17.6 DIN19537 R4 DN300 355x20.1 128
m 21.8.00
Handbeschriftung: Auslauf 12016, 28.8.2012

4.2.3 PP-B solid-wall sewer pipes from Norway, pipe code N1

Solid wall sewer pipe with a diameter of 110mm was installed in the year 1989 in the village of Vanvikan. The pipe is a black PP-B impact block copolymer. The picture of the pipe is shown in figure 4.8 and figure 4.9.3

The reddish colour on top of the pipe is dirt from the ground, most probably clay. The outer surface has scratches either from the installation or excavation. There were some stress whitening marks in the inner surface of the pipe: one was continuous along the extrusion axis, other stress whitening marks were localised and intermittent.

Pipe code	N1
Location:	Vanvikan community
Soil type:	Sand, with some stones in the backfill causing point loads
Deflection after recovery:	1.5-2.0 %
System:	sewer from one family house
Installation depth:	1.2 meter
Pipe installed in	1989 (23 years in operation)
Pipe material:	PP-B with master-batch/colour
Pipe type:	110 x 3.8mm, pipe class S14



Figure 4.8 Pipe N1, PP solid-wall 110mm

Figure 4.9 Excavation sites in Norway



Figure 4.9.1

Excavation of 160mm structured-wall pipes in Surnadal Norway, Pipe N2



Figure 4.9.2
Excavated 160mm PP structured-wall pipe from Surnadal, Pipe N2



Figure 4.9.3
Excavated 110mm PP solid wall pipe from Vanvikan Norway, Pipe N1

4.2.4 PP-B structured-wall sewer pipes from Norway, pipe code N2

The pipe with a diameter of 160mm was installed in 1991 in Surnadal in Norway. The pipe is produced from a PP impact block copolymer. The pipe has a corrugated external surface with smooth inner surface, both terracotta coloured. The picture of the pipe is shown in figure 4.9.1 and 4.9.2

The white and orange marks on the outer surface are traces of paint, see figure 4.10. There are only minor scratches on the ribs from either installation or excavation of the pipes.

In the inner surface there is more brownish area on one side of the pipe. It seems that this was caused by the sewer water.

The brownish area can be seen between measurement positions 8-1, see figure 4.11.

Pipe code	N2
Location:	Surnadal, in a slope of 15 %
Soil type:	0.5m fine grained gravel backfill
Deflection after recovery:	0.4 - 2.1%
System:	sewer water from 20 households
Installation depth:	1.3m
Pipe installed in	1991 (20 years in operation)
Pipe material:	PP-B
Pipe type:	DN/OD160, inside diameter 140mm



Figure 4.10 Structured-Wall Pipes from Norway, pipe N2



Figure 4.11 Pipe with brownish surface

4.2.5 PP-B structured-wall pipes from Denmark, pipe code D1

The structured wall pipe with a diameter of 200mm has a terracotta colour on the geometrically structured external surface and has a white smooth inner surface. Pipe was taken in use in 2004 so it has been in use 8 years. The pictures of the pipe is shown in figure 4.12 and 4.13. The black “stripe” on the outer surface seems to be some kind of paint. Outer surface has only small/minimal marks on the ribs from installation or from excavation. Inner surface shows no marks of abrasion.

Pipe code	D1
Location:	Skyve
Soil type:	Clay/sand with sand backfill
Deflection after recovery:	None
Installation depth:	2.5m
Pipe installed in	2004 (8 years in operation)
Pipe type:	DN200mm SN8 structured-wall pipe



Figure 4.12
Excavated Pipes from Denmark



Collected pipe samples



Structured-Wall pipe in the trench



Excavation site

Figure 4. 13 Excavation site in Skyve, Denmark

4.3 Test methods

Different test methods were applied to characterize the properties of the excavated pipes. Beside this, the resistance to thermo-oxidative degradation, the residual stresses, the longitudinal shrinkage and the deflection were determined. From the time to failure a life-time prediction for PE pipes was made based on Arrhenius model.

The test methods applied are described in the following clauses.

4.3.1 Material characterization

Samples were taken from the pipe at different positions as shown in figure 4.14 to perform the described tests. The top and bottom positions could be easily defined as the deposits in the pipe clearly marked the flooded area.

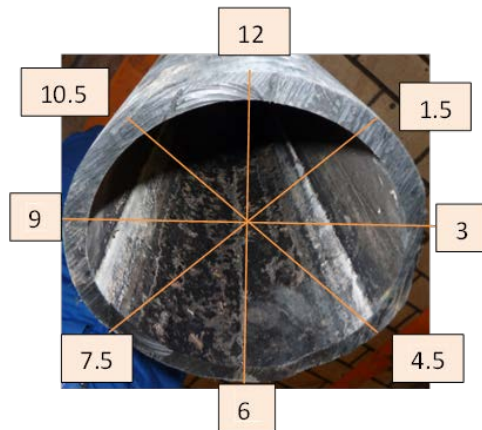


Figure 4.14 Defined positions over the circumference

4.3.2 Internal pressure tests

Pipe pressure tests for the PE pipes at 80 °C with a $\sigma = 2.8$ MPa and for the PP-B pipes at 95 °C with $\sigma = 2.5$ MPa were performed according to ISO 1167-1:2006 [24] to predict the remaining life-time in regard to the resistance to slow crack growth (SCG).

4.3.3 MFR

The Melt Flow Rate (MFR) was determined on samples from the pipes according ISO 1133 [25], for PE pipes at 190 °C and a load of 5 and 21.6 kg. For PP-B pipes at 230 °C with a load of 2,16 kg.

4.3.4 Intrinsic viscosity (IV) of PE pipes

About 100 μm thick samples were taken from the internal surface, mid wall and from the external surface of the pipes to determine the reduced viscosity according to ISO 1628-3:2010 [26]. The viscosity was determined on 0.1 % solution decahydronaphthalin at 135 °C.

4.3.5 Gel-Permeation-Chromatography (GPC)

Gel permeation chromatography (GPC) was used for characterizing of the molecular mass distribution of the pipe materials to identify the polymer composition. In ISO 16014-1 [27] the determination of average molecular mass and molecular mass distribution of polymers using gel-permeation-chromatography is described.

4.3.6 FT-IR-Spectroscopy

The ATR-technique was used to detect thermo-oxidative degradation at the internal surface of the pipes. Furthermore FT-IR spectroscopy was used to determine the presence of co-monomer in the pipe material.

4.3.7 Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) was used to measure the thermal transitions, such as melting and re-crystallization and the enthalpies of these transitions. DSC measurements were performed in accordance with EN ISO 11357-1:2010 [28] with a heating rate of 10K/min and a sample weight of about 6 mg.

4.3.8 Full notch creep test on PE pipes (FNCT)

The FNCT was determined as described in ISO 16770:2004 [29].

4.3.9 Oxidation stability (OIT)

The oxidation stability has been evaluated through Oxidation Induction Time (OIT) at 200 °C for PE samples and 210 °C for PP samples, under oxygen by means of Differential Scanning Calorimetry (DSC) according to ISO 11357-6 [30]. For that reason samples were taken at different positions from the pipe wall and the OIT was determined isothermally. The measurement was performed with an automatic gas switch was used.

4.3.10 Longitudinal shrinkage of PE pipes

The longitudinal shrinkage test was performed as described in EN 12666-1:2011 [4] at 110 °C according to EN 743:1994, method B [31].

4.3.11 Residual stresses of PE pipes

The frozen-in residual stresses have been evaluated by means of the well-known ring closing test at 23 °C, which involves measuring the closing variations with time of a pipe section after extraction of a 30-to-60° sector. The remaining residual stresses in the excavated pipes were determined using the method described in [14]. As shown in figure 4.15 a segment of 60 mm was cut out from a pipe section (Length: 200 mm) and the resulting deformation was determined as a function of time after 3, 60 (1 hour) and 1440 minutes (24 hours).

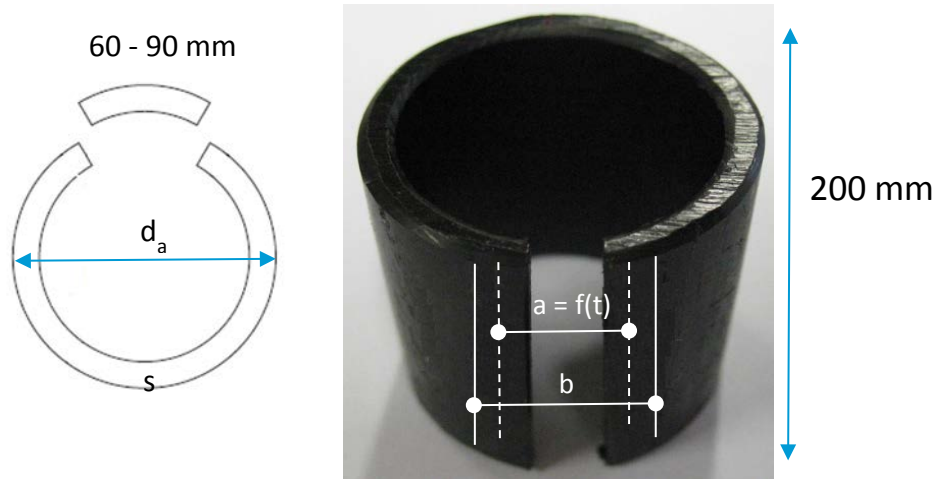


Figure 4.15: Principle of determination of residual stresses

For that reason the pipe segment was kept under constant climate conditions (23 °C; 50 % rel. humidity). The distance between two markings which were applied in a distance of 10 mm along the segment was measured before and after removal of the segment. The residual stresses in the pipe can be estimated by use of the equation:

$$\sigma_E = \frac{b - a}{\pi \cdot (d_a - s) \cdot s} \cdot \frac{s}{d_a - s} \cdot E \quad [\text{MPa}]$$

Where:

- b Distance between the markings before cutting,
- a after defined time determined distance between the markings,
- d_a outer pipe diameter,
- s wall thickness,
- E after defined time determined creep modulus

4.3.12 Flexural creep modulus of PE pipes

The flexural creep modulus was determined according to ISO 899-2:2003 [32]

4.3.13 Heat ageing at PE pipes

The heat ageing was done on specimen (20 x 200 mm) cut from the pipe at 100 °C and 120 °C in a ventilated oven until brittle cracks in could be observed after bending the specimen.

4.3.14 Ring stiffness, ring flexibility and Impact tests of PP-B pipes

Tests are carried out according to the procedures described in EN1852-1 [5] and EN13476-3 [6].

5 Results

5.1 PE solid wall sewer pipes, code F1

5.1.1 Material characterization

The pipes were probably produced from a PE63 HDPE pipe material, which was a common HDPE pipe material until 1978. Different methods were applied to characterize the pipe material which had been in service for about 38 years. In table 5.1 OIT, MFR, density and further test results are listed. The MFR (190 °C; 5 kg) at position 6 and 12 is 0.39 g/10min and slightly higher as specified for 1st generation HDPE pipe resins with a MFR (190 °C; 5 kg) of 0.3 g/10min. Yet this slightly higher MFR is not related to polymer degradation as the values for OIT and intrinsic viscosity support. The density was 0.957 g/cm³ is in accordance with the specified density of 0.955 g/cm³ of the original material taking in account the different annealing procedure at that time.

Table 5.1, test results PE pipe F1

Properties	Unit	Method	Position 12			Position 6		
			E	M	I	E	M	I
Intrinsic viscosity (IV)	dl/g	ISO 1628	3	2.8	2.8	2.8	2.8	2.8
OIT (200 °C)	min	EN 728	21	29.5	23	37	26	18
MFR (190 °C/5 kg)	g/10 min	ISO 1133	0.39			0.39		
Density	g/10 min	ISO 1133	0.957			0.957		
Melting point ¹⁾	°C	ISO 11357-1	129			127		
Heat of fusion ¹⁾	J/g	ISO 11357-1	180			181		
FNCT (4 MPa, 80 °C , 2 % Arkopal)	h	ISO 16770	1.8			2.1		
Tensile modulus	MPa	ISO 527	821			979		
Tensile strength at yield	MPa	ISO 527	23.7			23.8		
Elongation at break	%	ISO 527	580			670		
Carbon black content	%	ISO 6964	2.35			2.35		

Legend:

1) from 1 st heating run

E = External surface

M = Mid wall

I = Internal surface

5.1.2 Gel-permeation-chromatography (GPC)

From a specimen taken from the internal surface at different positions of the pipe the molar mass distribution has been determined by GPC. As shown in figure 5.1 the obtained GPC curves from samples taken at position 6 and 12 are quite similar and are conform to that from the original material. As the GPC curves from samples taken from clock position 6 and 12 do not differ it is obvious that the contact with sewer water did not accelerate polymer degradation. This finding is supported by OIT and intrinsic viscosity values reported in chapter 5.1.4.

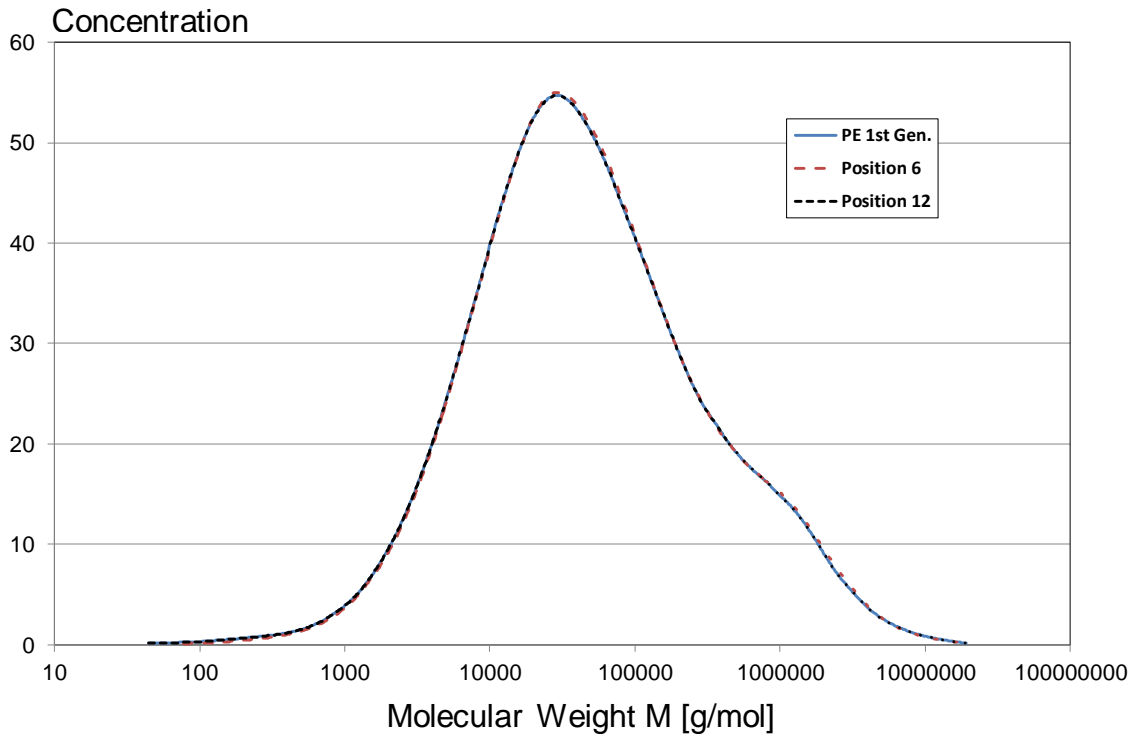


Figure 5.1: GPC data from samples taken from internal pipe surface vs. original PE grade of the first generation

5.1.3 FT-IR spectroscopy

The FTIR spectra do not show characteristic carbonyl absorptions of oxidized PE chains at wave number 1720 cm^{-1} (see figure 5.2). Though the internal surface was cleaned the ATR spectra mapped from the internal surface at position 6 shows some additional absorptions compared to those from mid wall and external surface at same position resulting from remaining deposits.

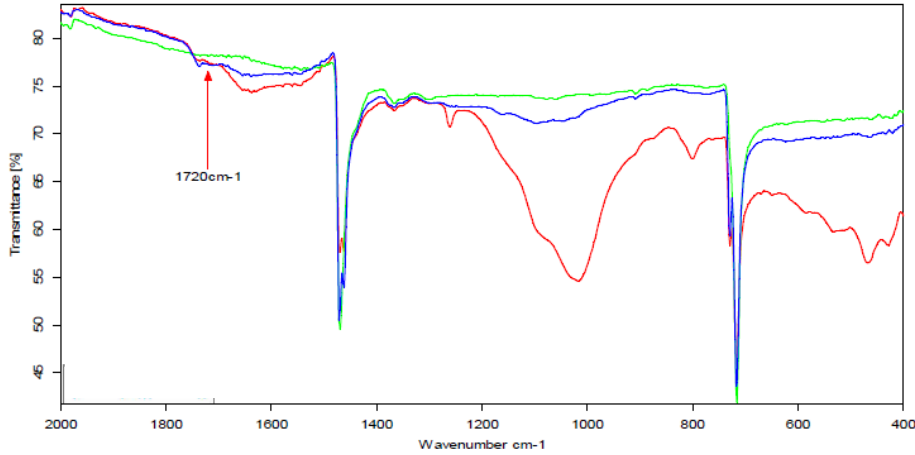


Figure 5.2: FT-IR spectra (ATR-technique) from samples taken at position 6: External surface (red), mid wall (green) and internal surface (blue)

5.1.4 OIT / Intrinsic viscosity

In table 5.2 are the obtained OIT and intrinsic viscosity (IV) values over the circumference are listed. The intrinsic viscosity of specimen taken from the surface or mid wall is quite similar, deducing that the area being in contact with sewer water during service didn't degrade the polymer. In contrast the OIT-values differ either in both circumference and wall position. Yet the measured OIT's of about 20 min demonstrate a still sufficient stabilization of the excavated pipes even after 38 years in service. The OIT-values from the outer surface are 17 – 24 min. over the circumference where those from the internal surface scatter between 20- 52 min, especially the highest OIT are obtained in the area with sewer water contact. The reason might be related to a faster migration of the present stabilizers to the internal surface at higher temperatures.

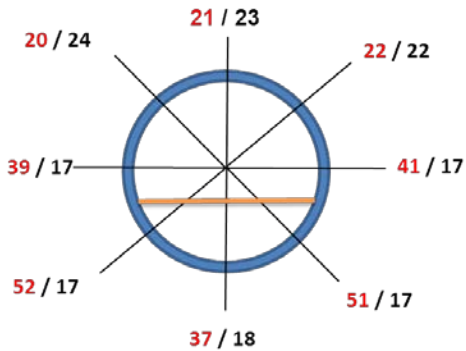


Figure 5.3: OIT from internal (red) and external surfaces (black)

Table 5.2: OIT and IV from specimen taken at different positions from the pipe

Clock position	OIT @ 200 °C [min]			IV [dl/g]		
	E	M	I	E	M	I
12	23	29	21	3	2.8	2.8
1.5	22	41	22	3	2.8	2.8
3	17	33	41	2.9	3	3
4.5	17	25	51	2.9	2.9	2.7
6	18	26	37	2.8	2.8	2.8
7.5	17	26	52	2.9	2.9	2.8
9	17	30	39	2.9	3.1	2.9
10.5	24	35	20	3.1	3	2.9

E = External surface
M = Mid wall
I = Internal surface

5.1.5 Pipe Dimension

Before measuring diameter and wall thickness the pipe surfaces were cleaned of deposits. The diameter was determined with 200.65 ± 1.25 mm and the wall thickness with 12.52 ± 0.14 mm. The wall thickness at different clock positions is shown in figure 5.4. The values demonstrate that wall thickness over the circumference is still quite consistent after 38 years in service and therefore abrasion by sewer water flow is negligible.

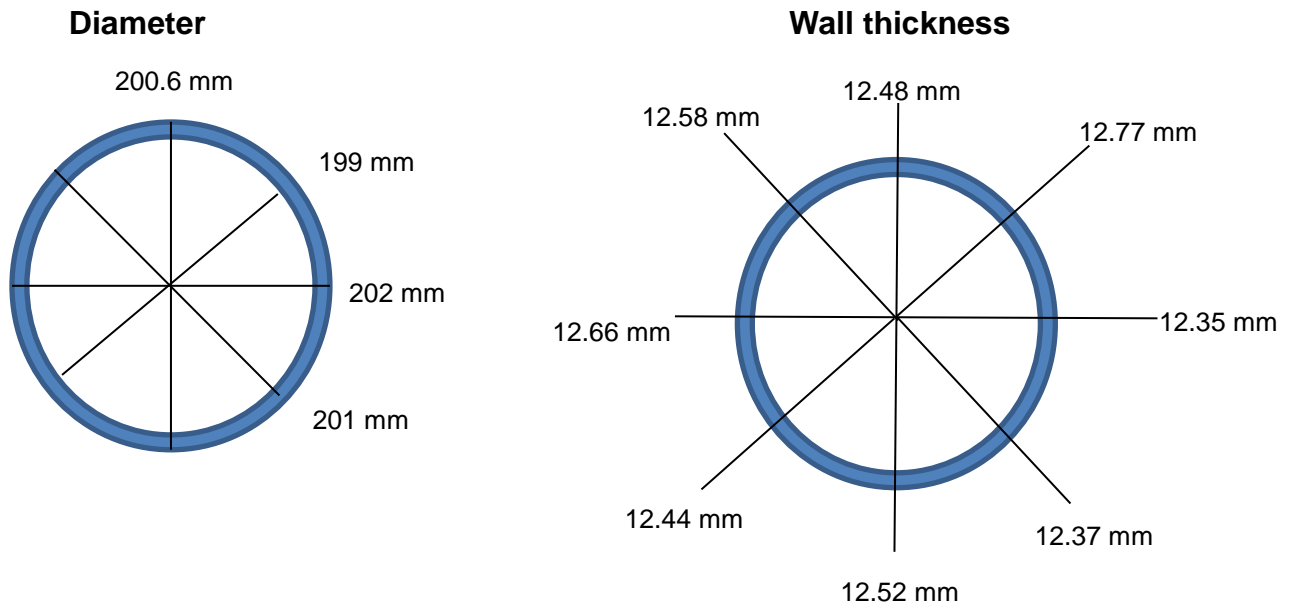


Figure 5.4: Wall thickness and diameter of the pipe at different positions over the circumference

5.1.6 Pipe deflection

The diameter of the pipe was measured at several positions as shown in figure 5.4. A deflection of only 3 mm or 1.5 % was determined which reflect excellent embedding condition.

5.1.7 Longitudinal shrinkage

The longitudinal shrinkage was determined on a pipe segment of 300 mm length which was kept for 120 min at 110 °C in a ventilated oven. Shrinkage of 1.6 % was obtained.

5.1.8 Residual stresses

The residual stresses were determined as described in chapter 4.3.11. The retaining of a segment from a pipe section affects a quick ring closure of the pipe section and a reduction of b (distance between the two markings) and the outer circumference C (table 5.3) which slows down with time as demonstrated for b in figure 5.5.

Time ¹⁾ [min]	Change of b with time [mm]	Circumference C [mm]
0	79,05	200,5
3	65,01	197,0
60	59,67	194,5
1440	50,12	190,6

1) Time after retaining the pipe section

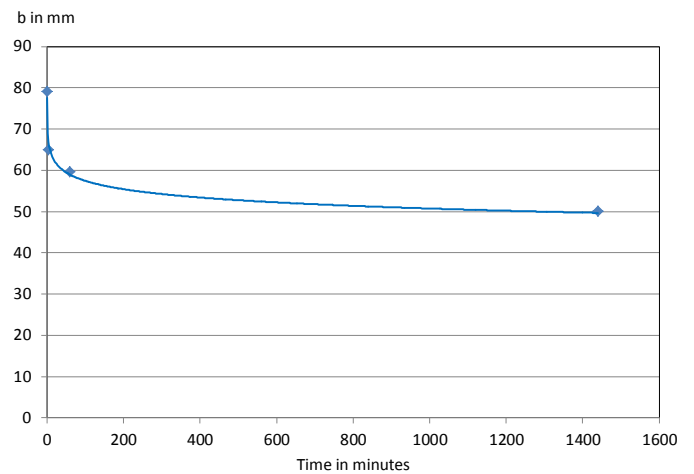


Table 5.3 Reduction of b and C after stress release

Figure 5.5 Reduction of b with time

The changes in b and C reveal residual compressive stresses in the pipe wall even after 38 years service life. As it is well known that internal stresses may affect slow crack growth it must be assured that the pipes resist such hoop stresses within a 100 years service-lifetime.

Assuming a perfect elastic behaviour of PE the residual stresses can be estimated using the equation given in chapter 2.4. For that reason the flexural creep modulus was determined in a tensile creep test at 23 °C till 24 h according ISO 899-2:2003 [32]. The calculated values of the compressive hoop stress at 23 °C are presented in figure 5.6. After 24 h (1440 min) the hoop stress reaches a value of about 1.6 MPa which is quite consistent with those found in literature.

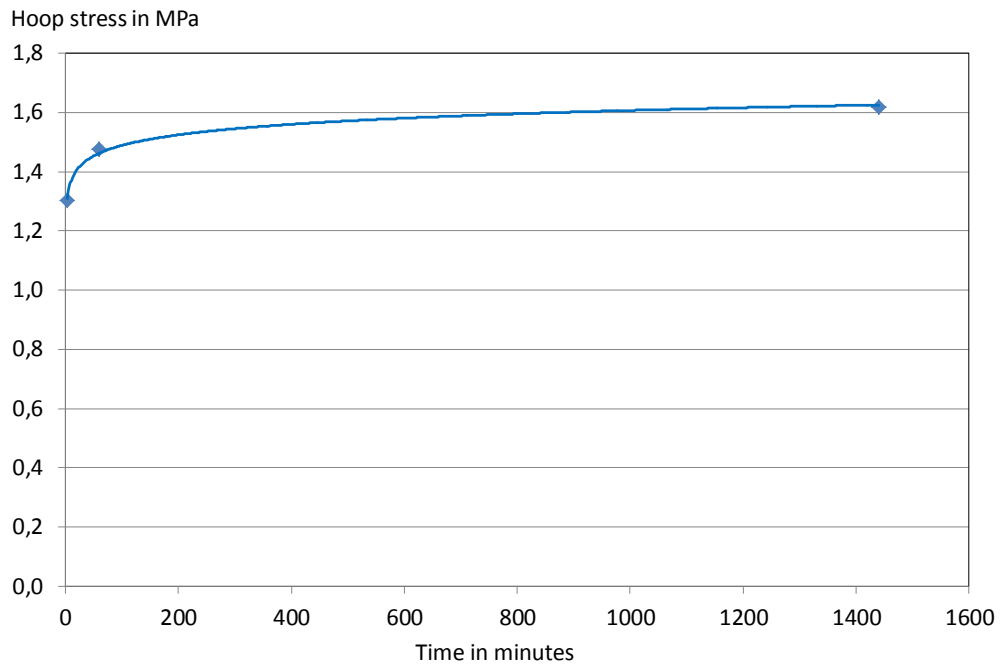


Figure 5.6 Compressive hoop stress calculated from ring closure test

5.1.9 Pipe pressure tests

Hydrostatic pressure tests were performed on the excavated pipes at 80 °C/ 2.8 MPa according to ISO 1167-1:2006 [24]. After 417 h, 584 h and 1034 h the pipes failed in stage II brittle mode due to slow crack growth. As shown in figure 5.7 these failure times (black dots) are quite similar those obtained from 1st generation (PE 63) HDPE pipes published by [9]. It is clearly understood that these results do not allow a lifetime prediction for the excavated pipes, because they do not represent a statistical data set as required in ISO 9080 [10]. However it suggests that during 38 years of service the physical properties of the pipe material didn't deteriorate.

Hoop stress in MPa

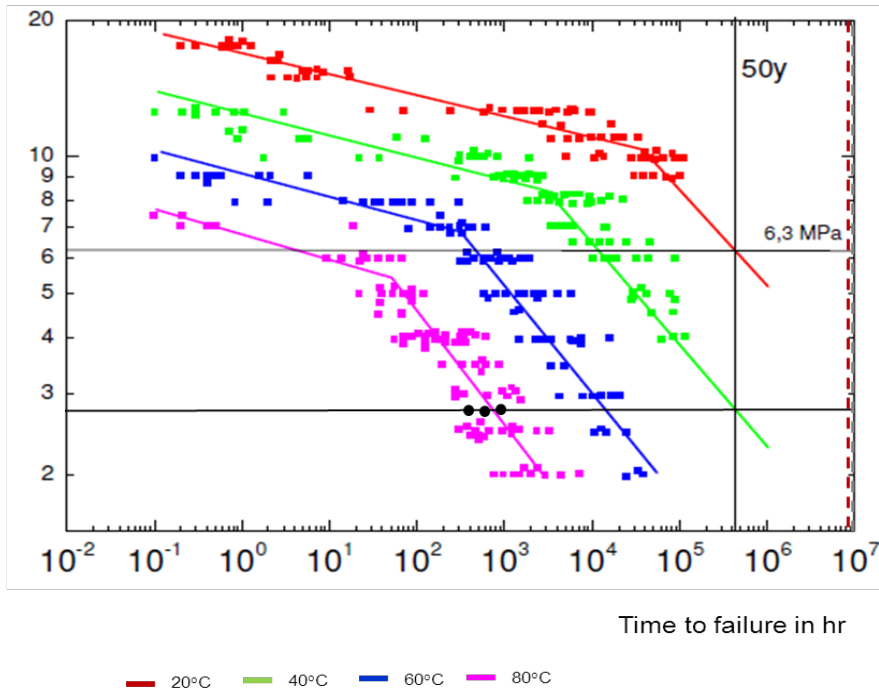


Figure 5.7 Hydrostatic pressure pipe test results from 1st generation HDPE pipe resins and 3 actual results from excavated pipes F1 (black dots at 2.8 MPa)

5.1.10 Residual ageing resistance

The heat ageing was performed on specimen prepared from the pipes at 100 °C and 120 °C as described in clause 4.3.13. The heat ageing was performed to estimate the residual lifetime in regard to thermo-oxidative degradation. The ageing results are listed in table 5.4.

Table 5.4: Results of accelerated heat ageing test

Ageing Temperature in °C	Time to failure in days
120 °C	27
100 °C	>205

Because sufficient stabilization was still present as implied by the high OIT values it took 27 days to embrittle the specimen at 120 °C. At 100 °C the specimen passed now more than 205 days without embrittlement. The mechanism of the degradation process is well understood and the activation energy E_A is within 90 - 95 kJ/mol for PE. From an Arrhenius plot the residual theoretical lifetime of more than 50 years at a service temperature of 45 °C can be derived as shown in figure 5.8. For the calculation activation energy of 90 kJ/mol and the time to failure from table 5.4 were used.

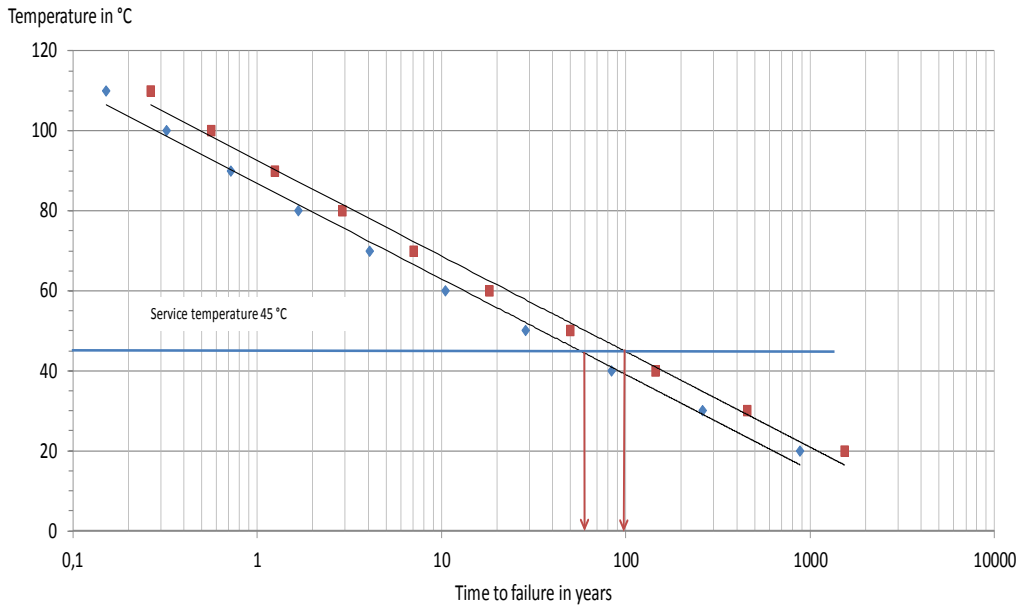


Figure 5.8 Lifetime estimation from heat ageing at 120 °C (blue) and 100 °C (red) using Arrhenius equation

5.2 PE solid wall sewer pipes, code G1, G2 and G3

5.2.1 Material characterization

5.2.1.1 Natural resin (internal) and black resin from dual-layer pipes

The dual-layer pipes consist of an internal layer of natural HDPE resin and an outer layer of black pigmented material. The pipe dimension is 355 x 20.1 and 280 x 15.9 mm. The thickness of the natural internal layer is about 3 mm for both dimensions. Both pipe dimensions were produced from PE 80 pipe resins. The properties of the resin used for the natural layer is of main interest because it was in contact with the sewer water. The measured properties suggest that the same resin was used (table 5.5). Because of the high amount of terminal C=C double bonds it is likely that the natural resins are made from chromium catalyst.

Table 5.5 Properties of the natural resin from dual-layer pipes

Properties of natural resin in dual-layer pipes	Unit	Method	Pipe 355 x 20.1 mm		Pipe 280 x 15.9 mm	
			Position 12	Position 6	Position 12	Position 6
Intrinsic viscosity (IV)	dl/g	ISO 1628	2.87	2.9	3.07	2.92
OIT (200 °C)	min	EN 728	> 120	> 120	82,3	17.1
MFR (190 °C/5 kg)	g/10 min	ISO 1133		0.48		0.47
MFR (190 °C/21.6 kg)	g/10 min	ISO 1133		9.36		9.32
Flow Rate Ratio (FRR)				19.5		20
Melting point ¹⁾	°C	ISO 11357-1		132		130
Heat of fusion ¹⁾	J/g	ISO 11357-1		205		194
Terminal C=C bonds (1/1000C)	%	LBI		1.24		1.22
Co-monomer		LBI		C ₆		C ₆

5.2.1.2 Black resins from mono-layer pipes

The properties of the black pipe materials are listed in table 5.6. Obviously two different materials have been used. The properties of the black material in the dual-layer pipes match those from a modern bimodal grade made in a reactor cascade, the 3rd generation HDPE pipe grade, and in the mono-layer pipe from a 2nd generation HDPE pipe grade.

Table 5.6 Properties of the black pigmented resins

Properties of black pigmented resin	Unit	Method	Black resin Mono-layer pipe	Black resin Dual-layer pipe	
				355 x 20.1 mm	280 x 159 mm
Intrinsic viscosity (IV)	dl/g	EN ISO 1628	2.6	3.1	3
OIT (200 °C)	min	EN 728	53	> 120	> 120
MFR (190 °C/5 kg)	g/10 min	ISO 1133	0.38	0.47	0.48
MFR (190 °C/21.6 kg)	g/10 min	ISO 1133	8.9	9.4	9.3
Flow Rate Ratio (FRR)			23.5	20	19
Density	g/cm ³	ISO 1183	0.955	0.958	0.958
Melting point (2 nd heating run)	°C	EN ISO 11357-1	128	129	129
Heat of fusion (2 nd heating run)	J/g	EN ISO 11357-1	183	195	197
Carbon black	%	ISO 6964	2.1	2.2	1.9

5.2.2 OIT/intrinsic viscosity

The intrinsic viscosities (IV) over the circumference from the natural layers of both pipe dimensions are quite similar and do not significantly vary between each position. Especially the areas which were in contact with the sewer water show similar IV's suggesting that the polymer has not started to degrade. The OIT values of the larger pipe are still very high and quite constant over the circumference (table 5.7). The pipe is still well protected against thermo-oxidative degradation. This is not the fact for the smaller dual-layer pipe dimension. In contrast to the larger pipe dimension are the obtained OIT's significantly lower and inconstant over the circumference. Especially at position 6 the OIT is dramatically lower as for all other positions. A reason might be a different flow rate and/or temperature of the sewer water. However, the mechanical integrity is still not effected and the values are still good. As both pipe sizes have been excavated at adjacent locations it seems obvious that the composition of the sewer water was the same.

OIT and IV were determined over the circumference and at different wall positions on the mono-layer pipe (table 5.7). The OIT values obtained from the external pipe surface are similar to those from mid wall position, yet those from the internal pipe surface are significantly lower, especially in clock position 4.5 and 6.

Table 5.7 Intrinsic viscosity (IV) and OIT over the circumference from dual-layer pipes

Position	Dual-layer Pipe Dimension 355 x 20,1 mm		Dual-layer Pipe Dimension 280 x 15.9 mm		Mono-layer Pipe Dimension 280 x 15.9 mm					
	OIT @ 200 °C [min.] I	IV [dl/g] I	OIT @ 200 °C [min.] I	IV [dl/g] I	OIT @ 200 °C [min]			IV [dl/g]		
					E	M	I	E	M	I
12	> 120	2.9	82	3	55	57	37	2.6	2.6	2.6
1.5	> 120	2.85	86	3	55	57	40	2.8	2.7	2.5
3	> 120	2.8	68.5	2.9	54	56	38	2.4	2.4	2.5
4.5	117	2.9	47	2.9	51	50	26	2.4	2.5	2.5
6	> 120	2.9	17	2.9	44	45	24	2.6	2.6	2.6
7.5	> 120	2.85	60	3	49	49	32	2.6	2.6	2.6
9	> 120	2.9	55.5	3	52	53	35	2.6	2.6	2.6
10.5	> 120	2.9	70	3.1	55	55	35	2.6	2.5	2.4

E = External surface

M = Mid wall

I = Internal surface

5.2.3 FT-IR spectroscopy

The FTIR spectra do not show characteristic carbonyl absorptions of oxidized PE chains at wave number 1720 cm⁻¹ (see figure 5.2). This is obvious because of the measured OIT values which already confirm a sufficient protection against thermo-oxidative degradation.

5.2.4 Pipe Dimensions

Before determining the diameter and wall thickness the pipe surfaces were always cleaned from deposits. The measured diameters and wall thicknesses are listed in table 5.8. The wall thickness exceed the required standard values of 20.1 or 15.9 mm. The deviations over the circumference are low.

Table 5.8 Determined diameter and wall thickness of excavated pipes G1, G2 and G3

Construction	Pipe code	Dimension * (mm)	Diameter (mm)	Wall thickness (mm)
Coextruded Pipe	G1	355x20.1	355 ± 1	21.18 ± 0.13
Coextruded Pipe	G2	280x15.9	280 ± 1	16.81 ± 0.37
Soli-wall Pipe	G3	280x15.9	281± 2	16.48 ± 0.24

*) as marked on the pipes

5.2.5 Deflection

The diameter of the pipe was measured at several positions as shown in table 5.9. For the dual-layer pipes a deflection of max. 2 mm or 0.6-0.7 % was determined and for the mono-layer pipe a deflection of max. 4 mm or 1.4 % was determined.

Table 5.9 Pipe deflection of excavated pipes G1, G2 and G3

Construction	Pipe code	Dimension (mm)	Pipe deflection (%)
Coextruded Pipe	G1	355x20.1	0.6
Coextruded Pipe	G2	280x15.9	0.7
Monolayer Pipe	G3	280x15.9	1.4

5.2.6 Residual stresses

The residual stresses were determined as described in chapter 4.3.11. The retaining of a segment from a pipe section affects a quick ring closure of the pipe section and a reduction of b (distance between the two markings) and the outer circumference C (table 5.10) which slows down with time as demonstrated for b in figure 5.9.

Table 5.10 Reduction of b and C after stress release

Time ¹⁾ [min]	Dual-layer pipe		Mono-layer pipe
	355 x 20.1 mm b in mm	280 x 15.9 mm b in mm	280 x 15.9 mm b in mm
0.1	146.42	146.42	142.47
3	100.2	99.76	92.75
60	93.84	87.57	82.25
1440	53.6	64.32	57.73
2880	39.7	54.89	47.4

1) Time after retaining the pipe section

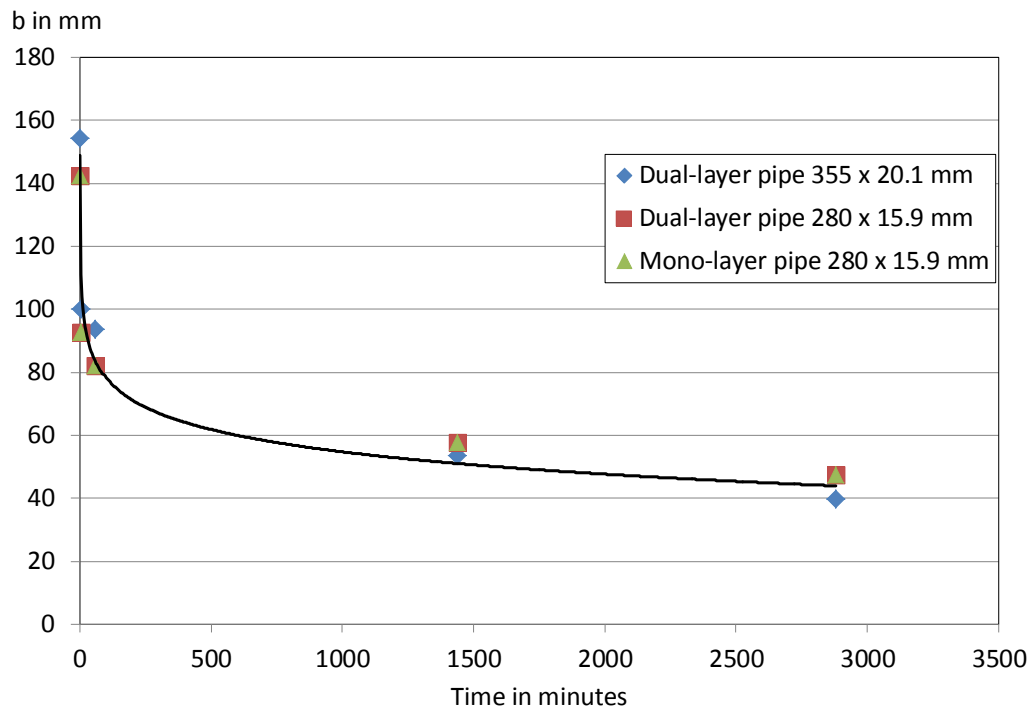


Figure 5.9 Reduction of b with time release

The changes in b reveal residual compressive stresses in the pipe wall even after about 16-18 years' service life. The calculated values of the compressive hoop stress at 23 °C using a creep modulus of 470 MPa. After 24 h (1440 min) the hoop stresses for excavated pipes with dimension 280x15.9 mm are 4.1 MPa and 4.2 MPa and for dimension 355x20.1 mm 2.0 MPa. This seems feasible because a higher stress relaxation during the extrusion process must be considered for larger pipes.

5.3 PP solid wall sewer pipes 110 x 3.8mm, code N1

5.3.1 Material Characterization

The mono-layer solid wall pipes were produced out of PP-B with 6,81 w-% ethylene. The MFR (230 °C and 2,16 kg) was 0,64 g/10 min for outer surface and 0,61 g/10 min for inner surface. Melting temperature for the outer surface was 161,5 °C and crystallization temperature 111,3 °C, and for inner surface the melting temperature was 160,6 °C and crystallization temperature 112,2 °C.

5.3.2 Pipe dimensions

Before the measuring the diameter and wall thicknesses the pipe surfaces were cleaned from deposits. The wall thickness measurement positions are shown in figure 5.10. Pipe diameters were measured between positions 1 and 5 : inner diameter was 103.57 mm and outer diameter was 111.44 mm.

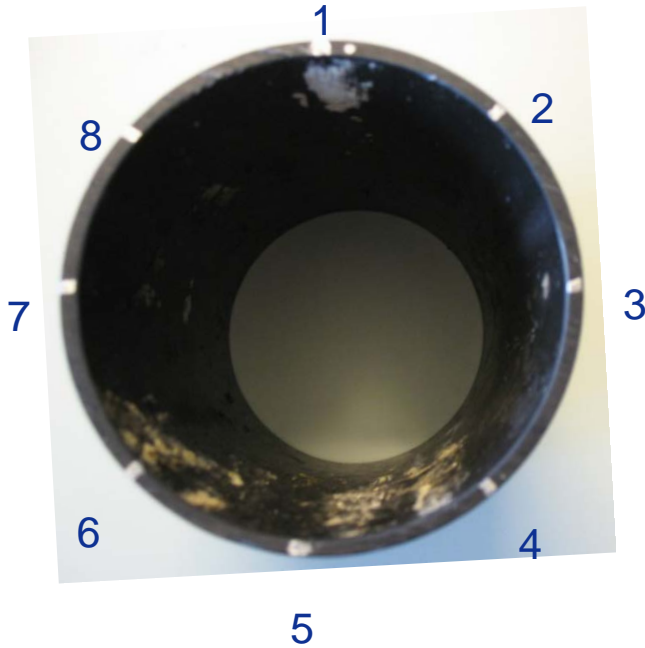


Figure 5.10 Wall thickness measurement positions

Wall thicknesses in the different positions of the pipe are collected to table 5.11.

Table 5.11 Pipe Black wall thicknesses in different positions

Wall thickness, mm	
1	4.10
2	4.11
3	4.24
4	4.08
5	4.03
6	4.07
7	4.01
8	4.02

According to the wall thicknesses, the deviation in thickness does not seem to be related to abrasion due to usage since wall thickness in positions 4 and 5 the wall is thinner (4.08mm and 4.03 mm respectively) compared to positions 7 and 8 (4.01 mm and 4.02 mm respectively). The

dirt seems to be mostly between the measuring positions 4 and 6, so if the abrasion was due to usage, the pipe should be thinner under those positions than under positions 7 and 8. Maybe the extrusion process caused the variation in the wall thicknesses.

5.3.3 Pipe deflection

The deflection of the pipes after excavation has been measured from 1.6 - 2.0 %

5.3.4 OIT and additive analysis

The OIT (210 °C/O₂) for outer surface was 7 minutes and for inner surface 3 minutes. According to additive analysis (HPLC) there was only Irganox 1010 present, the concentration in outer surface was 1135 ppm and in inner surface 850 ppm. According to gas chromatography there is 2392 ppm DSTDP stabiliser left in the outer surface and 2429 in the inner surface.

5.3.5 Ring stiffness and ring flexibility

The ring stiffness was 5.7 kN/m² and the ring flexibility was 36.4 %.

5.3.6 Falling weight test

In falling weight test the maximum height was 2820 mm with 8 kg at – 10 °C

5.3.7 Internal pressure tests

The results of internal pressure tests at 95 °C /2,5 MPa are given in table 5.12

Table 5.12, Internal hydrostatic tests at 95 °C / 2,5 MPa

Ø 110x3.8 mm

Test temperature: 95 °C

Sample no	Mean outside diameter mm	Min. wall-thickness mm	Hoop stress MPa	Internal pressure Mpa	Time to rupture h	Failure type h
1	110.1	3.95	2.5	0.186	1260	Brittle
2	110.1	3.95	2.5	0.186	>2800	Interrupted
3	110.1	3.95	2.5	0.186	>2800	Interrupted

5.4 PP-B structured-wall sewer pipes DN/OD 160, code N2

5.4.1 Material Characterization

The pipes were produced out of PP-B with ethylene content of 8.85 w-% in the outer geometrically structured surface and 9.22 w-% in the smooth inner surface. The MFR (230 °C and 2.16 kg) was 0,39 g/10 min for outer surface and 0.47 g/10 min for inner surface.

Melting temperature for the outer surface was 159.2 °C and crystallization temperature 113.5 °C, and for inner surface the melting temperature was 159.8 °C and crystallization temperature 112.9 °C.

5.4.2 Pipe dimensions

Before the measuring the diameter and wall thicknesses the pipe surfaces were cleaned to remove deposits. The wall thickness measurement positions are shown in figure 5.11. Pipe diameters were measured between positions 1 and 5 (similar to figure 5.10), inner diameter was 140.37 mm and outer diameter was 160.21 mm

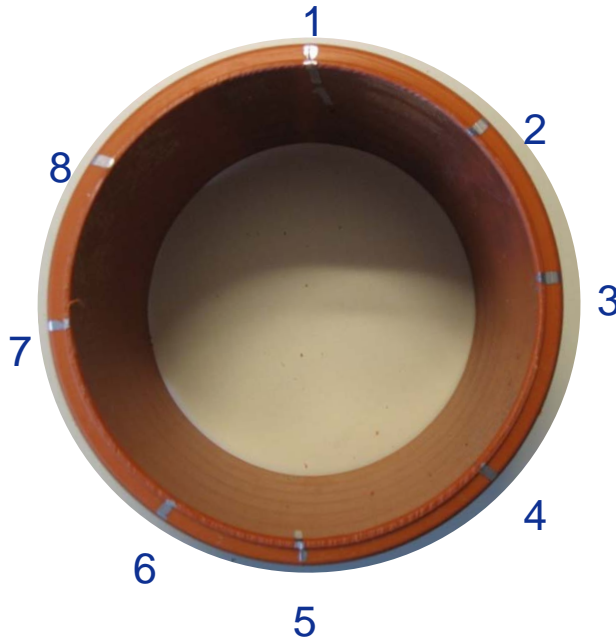


Figure 5.11 Wall thickness measurement positions

Wall thicknesses in the different positions of the pipe are collected to table 5.13.

Table 5.13 Pipe cloak wall thicknesses in different positions

Wall thickness, mm	
1	2.15
2	2.55
3	2.43
4	2.27
5	2.63
6	2.60
7	2.25
8	2.42

As it can be seen in the figure 5.11, there are no traces of use in the inner surface. The same indication is gotten from the table 5.13, where there is no clear reduction of the wall thickness in some of the pipe sections.

The height of the outer profile was 9.77 mm, the inner 6.82 mm and the wall thickness of the profile was 1.75 mm (point 12). Wall thickness between the ribs was 2.18 mm (point 9) and 2.20 mm (point 11), and inside 1.20 mm (point 10). The measurement points are shown in figure 5.12.

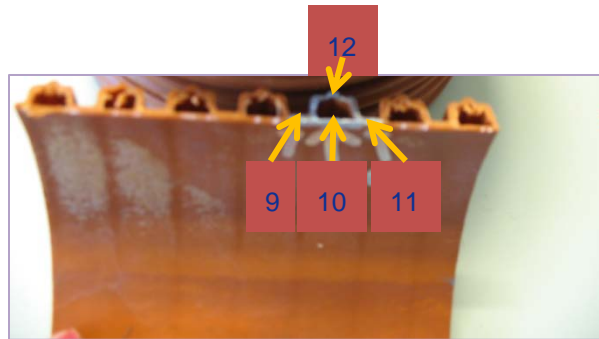


Figure 5.12 Pipe wall thickness measurement points around the profile

1.1.1 OIT and additive analysis

5.4.3 OIT and additive analysis

The OIT (210 °C/O₂) for outer surface was 6 minutes and for inner surface 5 minutes. According to additive analysis (HPLC) there is Irganox 1010 both in inner (1258 ppm) and outer surfaces (1300 ppm) but only Irgafos 168 in the outer surface (106 ppm). According to gas chromatography there is 2450 ppm DSTDP (**thioester auxiliary antioxidant**) stabiliser left in the outer surface and 2449 ppm in the inner surface.

5.4.4 Pipe deflection

The deflection of the pipes has been measured after excavation from 0.4 to 2.1 %

5.4.5 Ring stiffness and ring flexibility

The ring stiffness was 7.9 kN/m² and flexibility 43.8 %.

5.4.6 Falling weight test

In falling weight test the maximum height was 984 mm with 8 kg at – 10 °C.

5.5 PP-B Structured-Wall sewer pipes DN/OD 200, code D1

5.5.1 Material Characterization

The pipes were produced of PP-B with 4.48 w-% ethylene in the outer surface and 12.65 w-% of ethylene in the inner surface. The MFR (230 °C and 2.16 kg) was 0.51 g/10 min for outer surface and 0.34 g/10 min for inner surface.

Melting temperature for the outer surface was 167.7 °C and crystallization temperature 128.1 °C, and for inner surface the melting temperature was 165.7 °C and crystallization temperature 122.5 °C.

5.5.2 Pipe dimensions

Before measuring the diameter and wall thicknesses the pipe surfaces were cleaned from deposits. The wall thickness measurement positions are shown in figure 5.13. Pipe diameters were measured between positions 1 and 5 : inner diameter was 103.57 mm and outer diameter was 111.44 mm.



Figure 5.13 Wall thickness measurement positions for pipe D1

Wall thicknesses in the different positions of the pipe are collected to table 5.14.

Table 5.14 Structured Wall pipe D1, wall thicknesses in different positions

Wall thickness, mm	
1	3.90
2	3.76
3	3.57
4	3.46
5	3.92
6	3.88
7	3.73
8	3.91

There are no traces of usage in the inner surface of the structured wall pipe, also wall thickness measurement data confirms the same outcome. There is no decrease in wall thickness in specific section of the pipe.

The thickness of the structured wall was 3.32 mm, the height 11.33 mm and wall thickness between the ribs was 3.41 mm. The pipe surface structure is shown in figure 5.14.



Figure 5.14 Ribs of the Structured-Wall pipe D1

5.5.3 OIT and additive analysis

The OIT (210 °C/O₂) for outer surface was 17 minutes and for inner surface 25 minutes, which is significantly higher than samples N1 and N2. According to additive analysis (HPLC) there was Irganox 1010, Irgafos 168 and Irgafos 186OX present in both outer and inner surfaces. In the outer surfaces there was 1708 ppm Irganox 1010, 1249 ppm Irgafos 168 and 309 ppm Irgafos 186OX. In the inner surfaces there was 3183 ppm Irganox 1010, 1004 ppm Irgafos 168 and 574 ppm Irgafos 186OX.

According to gas chromatography DSTDP stabiliser was present only in outer surface in 1938 ppm concentration.

5.5.4 Ring stiffness and ring flexibility

The ring stiffness was 10.4 kN/m² and ring flexibility 45.1 %.

5.5.5 Falling weight test

In falling weight test the maximum height was 3325 mm with 10 kg at – 10 °C.

5.6 Summary of tests of excavated PP-B pipes

The materials used are heterophasic PP copolymers with an ethylene content in the range of 4 to 13w%. The materials used for the structured wall pipe are stronger nucleated than the others. The remaining content of antioxidants that have been found in the excavated pipes, is still at an exceptionally high level, this is indicating that over time not major loss of the stabilisation package has occurred. This is also indicated by the measured OIT values at the different layers. The mechanical testing showed that the structured wall pipe (SN8) and the solid wall pipe (SN6.3) are below their required level but this is related to the dimensioning and to the use of materials with lower stiffness, whereas the structured wall pipe D1 is above SN10, the ring-flexibility of all pipes is above 30 %. Falling weight test on the pipes showed that the impact performance at cold temperatures is given.

All tested pipes passed the required 1000 hours internal hydrostatic pressure test at 95 °C and 2.5 MPa.

Based on this it can be said that the used materials would still pass the relevant standards for non pressure sewage pipes.

All the test results of PP pipes are summarized in table 5.14.

Table 5.14 Summary of all the results of PP-B pipes

		Unit	Structured-wall DN 160 mm Code: N2		Solid-wall DN 110 mm Code: N1		Structured-wall DN 200 mm Code: D1	
			Outer layer	Inner layer	Outer layer	Inner layer	Outer layer	Inner layer
DSC	Melting temp.	°C	159.2	159.8	161.5	160.6	167.7	165.7
	Crystallisation temp.		113.5	112.9	111.3	112.2	128.1	122.5
OIT	210 °C/O ²	min	6	5	7	3	17	25
MFR	230 °C/2.16 kg	g/10 min	0.39	0.47	0.64	0.61	0.51	0.34
HPLC	AO 1	ppm	1300	1258	1135	850	1708	3183
	AO 2	ppm	106	X	X	X	1249	1004
	AO 3	ppm	X	X	X	X	309	574
GC	DSTDTP	ppm	2450	2449	2392	2429	1938	X
Spectroscopy	IR		PP-B (8.85 w%) Fe ₂ O ₃	PP-B (9.22 w%) Fe ₂ O ₃	PP-B (6.81 w%) Carbon black		PP-B (4.48 w%)	PP-B (12.65 w%)
Mechanic properties	Ringstiffness	kN/m ²	7.9		5.7		10.1	
	Ringflexibility	%	43.8		36.4		45.1	
	Falling weight - 10 °C/H50	mm	984 (8 kg)		2820 (8 kg)		3325 (10 kg)	

5.7 Final remarks

Using qualified polyolefin materials and pipes that are well extruded and installed according to good workmanship-practise, the test results of the 5 excavated PE and PP-B pipes have shown that polyolefin pipes are well qualified to reach a 100 years lifetime.

Even for the first generation PE, it became clear that after 38 years of operational use, a total lifetime approaching 100 years can be expected. PP-B materials up to 23 years operation time did not show any significant reduction of mechanical properties and stabilisation.

It is recommended to respect the conditions as defined in the conclusions in clause 1.2.

Annex, reports of investigations executed for this project

1. SP report "Stress relaxation tests", Sven-Erik Sallberg, SP Structural and Solid Mechanics, ref. PX25917B, 2013-04-30
2. SP report "Finite element analysis of double walled pipe- plastic material model", Daniel Vennetti, SP Structural and Solid Mechanics", ref. PX26221-1, 2013-04-17
3. SP report "Determination of resistance to internal pressure test on old excavated PP-pipes according to ISO1167-1: 2006, Lars-Gosta Petersson, SP Structural and Solid Mechanics, ref. FX21736A and FX21736B, Dec 2012.
4. TGM study "Literaturrecherche über die Inhaltstoffe von Abwasser und Untersuchung bzw. Recherche über die Temperaturprofile des häuslichen Abwassers", Dipl. Ing Edith Grüner, TGM Report VA KU 24585, (2013).
5. SP report "Stress relaxation tests - additional measurements" , Sven-Erik Sallberg, Structural and Solid Mechanics, ref. 4P02438, 2014-04-03

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2. ISO 8772:2006 "Plastics piping systems for non-pressure underground drainage and sewerage -- Polyethylene (PE)"
3. ISO 8773:2006 "Plastics piping systems for non-pressure underground drainage and sewerage -- Polypropylene (PP)"
4. EN 12666-1:2011-11 "Plastics piping systems for non-pressure underground drainage and sewerage – Polyethylene (PE) - Part 1: Specifications for pipes, fittings and the system"
5. EN 1852-1:2009-07 "Plastics piping systems for non-pressure underground drainage and sewerage – Polypropylene (PP) - Part 1: Specifications for pipes and fittings and the system"
6. EN 13476-3:2007-05 "Plastics piping systems for non-pressure underground drainage and sewerage – Structured-wall piping systems of non-plasticized poly(vinyl chloride) (PVC-U), polypropylene (PP) and polyethylene (PE) - Part 3: Specifications for pipes and fittings with smooth internal and profiled external surface and the system, Type B
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13. DIN 8075:2011-12, Polyethylene (PE) pipes: General quality requirements, testing
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16. *Structural integrity of PE gas/water pipes of the first generation*, by Frans Scholten et.al.
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20. DIN 8078, Polypropylene (PP) pipes - PP.H, PP-B, PP-R, PP-RCT - General quality requirements and testing
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