DURABILITY TESTING FOR 100 YEAR LIFETIME FOR BURIED NON-PRESSURE PLASTIC PIPES

Gunnar Bergström[1], Stefan Nilsson[1], Kristian Thörnblom[1]
Carl-Gustaf Ek[2], Harald Herbst[3], Anders Stenström[2],
[1] Swedish National Testing and Research Institute, Sweden
[2] Borealis AB, Sweden
[3] Borealis Polyolefine GmbH, Austria

ABSTRACT

For plastics pipes used for underground drainage and sewerage there is at present no internationally accepted method for the evaluation of durability. This makes it difficult to make an objective assessment for both new materials and new pipe designs entering the market. This paper presents a possible future structure of such a durability evaluation for non-pressure pipes.
Based on an experimental study of pipes made from a filled and an unfilled PP material and one made from an HDPE material different damage mechanisms and changes in pipe characteristics were observed when the pipes were exposed to long-term deflection and long term (one-year) ageing at +95 °C. A CAED methodology is also described which was used to investigate the distribution and time dependence of pipe stresses.

INTRODUCTION

For plastics pipes used for non-pressure underground drainage, sewerage and other non-pressure pipe applications there is at present no internationally accepted method for the evaluation of the durability of the material. In practice pipe material selection is based upon comparative operational experience of the different materials over a number of years and on material tests developed for pressure pipe materials. This means that there is no way of assessing durability for new pipe designs and new pipe materials that are introduced into the market. Whilst some recently introduced materials have superior properties in many respects and should perform well there are others of lower quality that may not achieve the required durability, e.g. recycled materials and inferior mineral filled materials. However with no recognised testing procedure it is not possible to rank these alternatives or restrict their application area without undertaking comprehensive end use testing.

It is well known that plastics pipe systems are well suited for use in underground pipe-work due to their flexibility to soil movements and their corrosion resistance etc. Pipe deflections of up to 10% can be accommodated as shown in the extensive studies performed by TEPPFA (1). The German ATV guideline accept a maximum pipe deflection of 9% (2), in ISO (3) the max long term value is limited to 10% deflection and in CEN (4, 5) it is stated that a deflection up to 15% will not affect the proper functioning of the pipe system. Not surprisingly flexible plastics pipes systems have a good track record and failure statistics (2, 6) providing confidence for all users of underground plastics pipes systems. It is also known that large diameter plastics pipe systems perform well in the soil (7). High quality pipes and pipe materials also perform well at high stresses and strains for long times (8-10).

However, what is not so well known is that the stresses in the pipe wall can still be relatively high after 10 or even 50 years of operation under these conditions. As expected the influence of soil pressure on the pipe system will reduce to a minimum after a few months after installation when the soil has settled (2, 8). However the pipe deflection remains constant after soil settlement and hence the stresses in the pipe wall will remain relatively high even though they will continue to relax with time. With some pipe structures and lower quality pipe materials (11), the stresses and strains in the pipe wall may possibly exceed the limiting properties of the material and thereby put the pipe system at risk from premature failure.

Ideally the durability evaluation of materials for non-pressure pipe systems should be based on one universal test method covering all relevant properties. This has been a subject of many expert discussions but it has proved difficult to find a way forward. Today the basic level of material performance for underground sewage and drainage piping is defined by the requirements in International and European standards (3-5, 12-15) including requirements on burst pressure strength and impact performance. For long term material durability, the focus of this paper is primarily the influence of the constant pipe deflection conditions and changes in the material due to ageing.

The target for the present work has been to form a durability evaluation concept based on a selection of key material characteristics and test methods. CAED techniques have been used to analyze how the stress field in the pipe develops with time.

MATERIAL DURABILITY EVALUATION METHODS

For evaluating the long term performance of the material, properties and test methods have been selected as presented in Figure 1. Despite the focus on material properties, pipe samples or samples from pipes have been used in order to come closer to the properties in the final application. Standardised test methods have been used as basis whenever possible.

Figure 1. Key performance characteristics for material durability for buried drainage and sewerage.

Key Performance Characteristic	**Method /Reference**	**Conditions**
Resistance vs. constant deflection (structural integrity)	Janson test (5) on virgin and water/air aged pipes. Ageing/extrapolation principles: EN ISO 9080	OD110 x 5 mm pipes, 23ºC 15, 25, 35, 45% pipe deflection Ageing: water/air 95ºC, 6 alt. 12 months
Notch resistance / Slow crack growth	ISO 13479 (80ºC/4.0 MPa, >165 h)	Water/Water 80ºC/4.2 MPa
Thermo-oxidative degradation	Ageing of pipe samples and measurement of mechanical properties & MFR. EN ISO 9080 extrapolation principles	Ageing: OD110 x 5 mm pipe samples in water/air 95ºC, 6 alt. 12 months.
Environmental stress cracking, ESCR	- ASTM D 1693, Bell test - ISO 13480, Cone test, (<10mm/day)	10% Igepal/50ºC 5% Arcopal/80ºC
CAED methodology	Under development	

Materials

The materials selected for these studies are representative of materials proposed in the market and have also been reported in a more extensive study of non pressure pipe materials (16).

Figure 2. Basic data for selected materials in the evaluation program.

Material	**PP-HM**	**Mineral filled PP-B**	**HDPE**	**Reference**
Type	PP-B (PP-HM)	PP-B + 30% talc	PE homo-polymer	
$MFR_{2.16}$ (g/10min)	0.3	0.6	0.5 (190ºC)	ISO 1133, 230ºC
Density (g/cm^3)	0.90	1.14	0.963	ISO 1183, 23ºC
E-modulus (MPa)	1700	2600	1500	ISO 527-2, 23ºC
Stress at Yield (MPa)	31	28	30	ISO 527-2, 23ºC
Notched Impact Strength (kJ/m^2) +23ºC - 20ºC	 50 5	 10 2	 15 12	ISO 179/1eA

Polypropylene block co-polymers, PP-B, are commonly used in Europe for underground drainage and sewerage applications, in-house soil and waste systems, cable protection and ducting pipe systems. PP-B materials have a track record of over 25 years for underground drainage and sewerage (17). In 2001 a CEN standard was also introduced for high modulus PP – PP-B (PP-HM) materials with a modulus of 1700 MPa or higher (5) and PP-HM is also included in other ISO and CEN documents (3, 4). The particular PP-HM grade used in this investigation was first introduced in 1997 and is now used for a wide range of structured-wall pipe systems and in large diameter spirally wound pipe (17-19).

Both the mineral filled PP material (designed for profile extrusion) and the very high density HDPE material (designed for blow moulding applications) have been included as these materials are commonly used for drainage and sewerage applications in some countries (depending upon national standards). The HDPE material is a homo-polymer and therefore lacks the co-monomer and hence the tie molecules which are essential for good ESCR and slow crack growth resistance, e.g. such as those materials used for modern bi-modal HDPE pressure pipe production. Mineral modified PP systems (PP-MD) have recently been covered within CEN standards for solid wall pipes (15). The requirements are basically on the same level as for non filled PP materials (5) except for an additional durability clause for the PP-MD systems. It should be noted that the mineral filled material in this study does not fulfil the prEN14758 (15) material requirements.

Resistance to constant deflection (structural integrity)

Long term integrity is undoubtedly the most important property for any pipe application (8). In the case of a non-pressure system the loading conditions may be regarded as almost pure constant deflection situation under which stress relaxation and any eventual damage accumulation occurs.

In testing, constant pipe deflections of 15, 25, 35 and 45 % were used and the force was constantly measured vs. time using force transducers and a data logging system. The 15% level was chosen as this is the highest level which is considered to be safe according to international standards (4, 5). The higher deflection levels were included to accelerate the processes and to allow for the higher local strains and stresses which are expected for structured-wall pipes. The underlying concept is that in the first step a relation between the deflection level and the time to failure is established. This relationship may then be adapted to a regression function from which life time can be predicted at a deflection of 15 %.

A limitation with stress relaxation testing is that it is difficult to extrapolate to longer time using time/temperature shift principles. This is mainly due to the temperature dependence of the relaxation modulus which will give a dramatic change in the stress field if the temperature is increased substantially (20).

Resistance to constant deflection on aged pipes

An alternative to the above longer term performance approach is to make tests before and after ageing of the samples in a similar way to that used for the evaluation of UV resistance in applicable standards and specifications. Evaluation is based on the performance before and after ageing in water at 95°C as defined in the recent European standard for mineral modified PP (15) and based on EN ISO 9080 extrapolation principles (21). The ageing was performed both in water and air, i e water outside and air inside (open end). Contrary to the specification no internal pressure was used in order to avoid additional influence of recovery during the relaxation test after ageing. Samples were also conditioned at 23°C for 1 month after ageing before any further testing was carried out.

Notch resistance / Slow crack growth

Notched pipe testing according to the principles in ISO 13479 were included in the program. For the HDPE material, the PE80 requirements were used (4.0 MPa un-notched pipe hydrostatic stress, 80°C, >165h) which is similar to the QC pressure testing requirement for sewage applications (4, 12, 13).

A slightly higher nominal un-notched pipe hydrostatic stress level is used for PP-HM and the filled PP material compared to the 4.0 MPa (80°C, >165h) requirement used for PE80 pipes. This is in order to have the same stress in the pipe wall (un-notched) as that in the QC pressure testing requirements at 80°C, i.e. 4.2 MPa, >140h for PP sewage applications (4, 5, 14, 15). Consequently it is possible to directly simulate the effect of external notches which could occur during installation on pipe performance. The notch depth of 20% of the wall thickness is also in line with notch depths observed in practice (22).

Thermo-oxidative degradation

Providing the material is sufficiently stabilised to cope with both high temperature processing and welding and for operation at up to 40°C, the thermo-oxidative degradation in air is normally not a problem. Compared to ageing in water, the degradation in air is usually of minor importance (16, 23) but for new materials and for recycled materials it can be important and therefore needs be considered.

The ageing method and type of pipe samples used are the same as described for the Janson test above, i.e. air inside and water outside. The change in mechanical properties before and after ageing 6 months or 12 months has been used for the evaluation, similar to the durability clause in EN14758 (15).

Environmental stress cracking, ESCR

Excellent ESCR properties are normal for PE pressure pipe materials and high quality PE and PP non-pressure materials. For non-pressure sewage materials it is important to have an easy evaluation method which indicates the sensitivity of the material to ESCR, especially when new pipe designs and new materials are introduced. Both the Bell bending test (ASTM D1693) and the Cone test (ISO 13480) which are used for PE80 and PE100 materials have been included. These tests have been selected because the stress relaxation conditions used in the test are close to the loading conditions for underground systems. Constant stress methods have also been shown to be effective for evaluation of finished pipes (24).

Computer simulation methodology

Computer Aided Engineering and Design (CAED) methodology was used for calculating the local stresses and strains in the pipe wall. The methodology is described in more detail in reference (25).

The calculations were made for pipe samples compressed between rigid plates, similar to a ring flexibility test. For the time dependant estimation of the local stresses and strains the program simulates 15 years of operation under stress relaxation conditions with an initial pipe deflection of 15%. Calculations are performed and compared to the experimental results for PP-HM and HDPE pipes.

The software-package of Abaqus 6.5-1 has been used. The input for the time dependant calculations was based on an elastic model together with general creep behaviour determined from tensile bars tested at several temperatures. At this stage in the analysis any possible effects from additional processing or material changes such as post crystallisation or non-uniformity of loading have been neglected.

RESULTS

Resistance to constant deflection (Structural integrity)

PP-HM materials

The stress relaxation curves for PP-HM with 15%, 25% and 45% deflection are shown in Figure 3. Figure 3a shows the relaxation modulus, E(t) vs. log time and Figure 3b the corresponding compliance curves (1/E(t) vs. log time) used by Janson (8). Curves are shown both for un-aged samples and for samples aged at 6 and 12 months in water/air at 95°C. Also plotted in the diagrams are results from another study (17) where 200 mm diameter PP-HM pipe samples have been under test since 1998 (i.e. under test for 8 years). The modulus and compliance curves show a similar behaviour for the un-aged samples with 15 % deflection as observed in the PP-HM reference curves from 1998, cf. Figure 3.

Using the principles of EN14758 testing 1 year aged samples should correspond to the behaviour of the pipe after at least 100 year lifetime, at temperatures usually seen for underground drainage and sewerage systems.

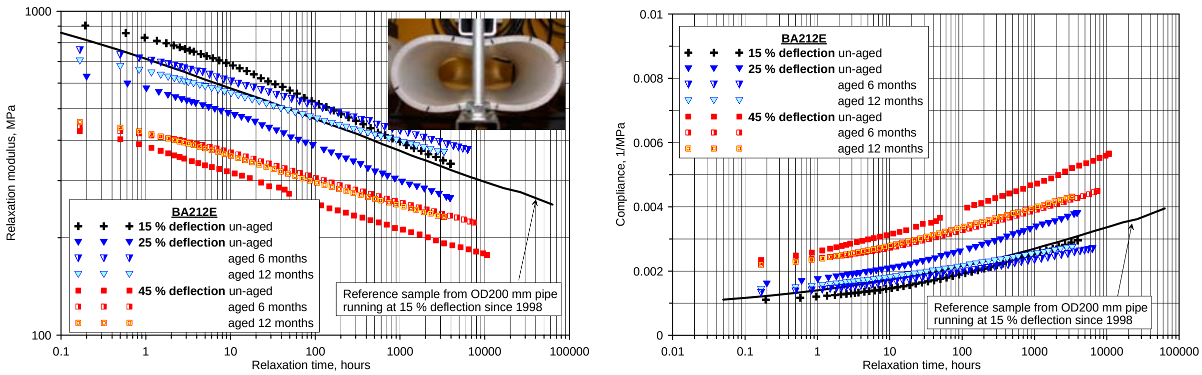

Figure 3. a) Modulus and b) compliance curves for OD110mm PP-HM pipes (aged/un-aged samples). Photograph of un-aged sample at 45 % deflection.

The aged pipes (25% and 45% deflection) show a lower initial compliance value and a more moderate slope with time. This observation is attributed to post crystallisation. The aged samples, both 6 and 12 months aged, are also reaching a rectilinear relationship within a shorter time period than for the un-aged samples. For the aged samples, the behaviour shows a linear relationship at an early stage.

The linear relationship between log time and compliance utilised by Janson (8), is less significant than that between log time and log modulus, i.e. the modulus curves in Figure 3 are straighter than the compliance curves.

Mineral filled PP-B

In spite of the 30 % mineral content, the compliance at 15 % deflection of the filled PP-B material on un-aged samples is greater than the corresponding results for the PP-HM material during the whole testing period, comparing Figures 3 and 4.

The relaxation behaviour for the un-aged and 6 months aged samples follows a similar pattern with respect to deflection level and post crystallisation as the PP-HM material. For 1 year aged samples the load bearing capability was drastically decreased with increasing deflection level. Visually an overall crazing behaviour was observed which was more pronounced at the positions with large strains, i.e. outside at clock position 3 and 9 and inside at 6 and 12. However, no concentrated cracks were observed during the measurement period for the un-aged pipes (up to 4000 hours).

The 1 year aged pipes show more pronounced crazing turning into small cracks at higher deflection levels. At 45 % deflection the crazing was observed during the loading phase and for the 35 % deflection, at around 300 hours after loading. It was also easy to remove a layer of the pipe surface by scraping. Since the material properties at the pipe surface are most important for the load bearing capability, the clear increase of the compliance with ageing time is also further supported by the visual ageing effects. No actual cracks were seen for the 6 months aged samples but crazing was observed as described above.

The increase in compliance could be attributed to debonding between filler and matrix. As known, debonding is more pronounced at higher strains, higher filler contents and longer test times (26). After ageing, an additional factor could be chemical breakdown of the matrix especially due to impurities in the filler.

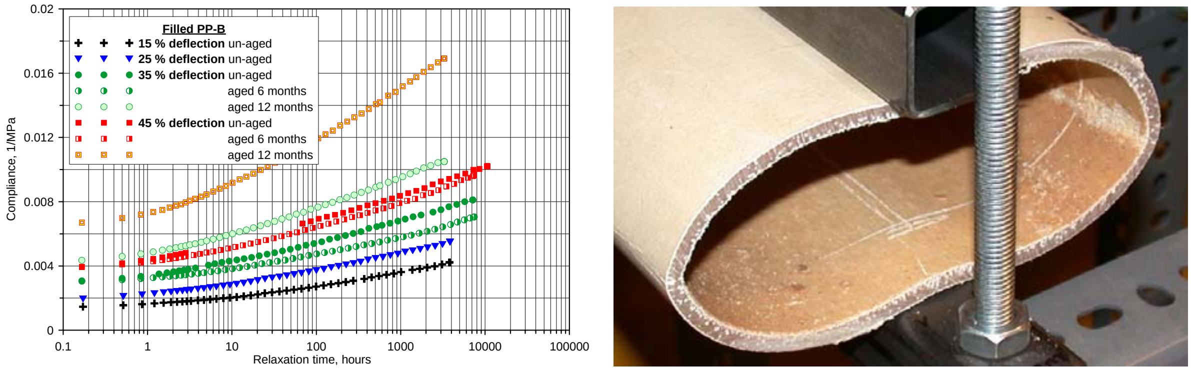

Figure 4. a) Compliance curves for OD110mm filled PP-B pipes (aged and un-aged samples), b) Photograph of sample aged 1 year at 45% deflection.

<u>*HDPE*</u>

The HDPE material tested shows a most interesting behaviour, see Figure 5. For both un-aged and aged samples the curves are reaching a rectilinear pattern very early as usually seen in PE materials. According to Janson (8), such linearity implies a stable behaviour without fracture, but that is not the case here. For un-aged samples, the first cracks were visible after 900 hours at 45 % deflection, 1400 hours at 35% deflection and 4500 hours at 25% deflection. At 15 % deflection the sample is still under test without cracks after 10000 hours.

There is a clear correspondence between the time to fracture and the deflection level, for both un-aged and aged samples. After ageing, both the crack initiation and propagation are accelerated as observed in the 6 months aged samples. The 12 months samples are sometimes showing longer times to crack initiation, compare also the mechanical test results in Figure 7 further below. The compliance curves for the 6 and 12 months aged samples have a less pronounced slope than the PP materials. The short term compliance is not significantly affected by ageing.

The difference between fracture times for 6 and 12 months aged samples can be attributed to the mixed degradation mechanism in the PE material, involving both chains scission and crosslinking.

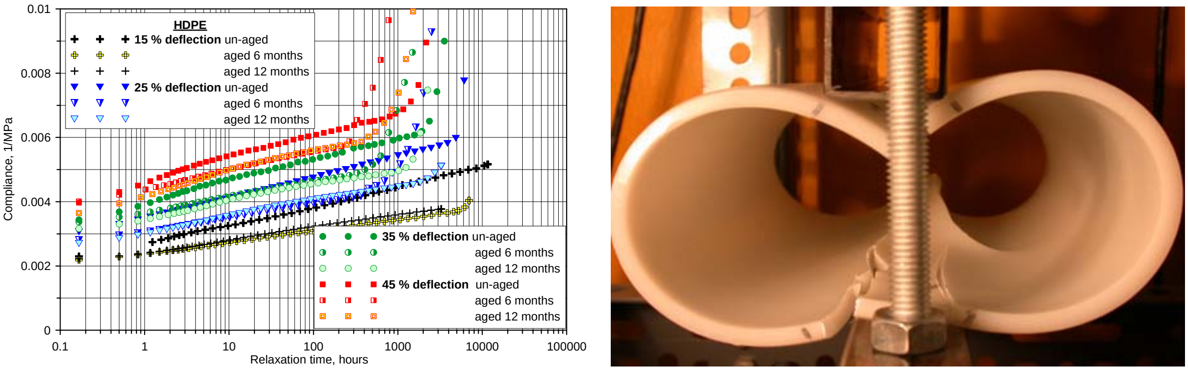

Figure 5. a) Compliance curves for OD110mm PE pipes (aged/un-aged samples), b) Photograph of un-aged PE sample at 45% deflection.

It should be noted that although the high stiffness HDPE material used for this study is in use for non-pressure pipes, it is not representative for materials used for PE pressure (PE80, PE100) pipes.

Notch resistance / Slow crack growth

Notch pipe results are shown in Figure 6. The nominal stress in the pipe wall is the same as for the QC pressure control points according to present standards (4, 5, 12-15). Consequently, the result will also be measure of the material resistance to external damage, in this case in the form of a sharp notch penetrating 20% of the pipe wall. As seen, the PP material is also passing the requirement with this type of sharp notch applied.

Material	**Hours to failure (h) (average of 2 samples)**
PP-HM	1423
Filled PP-B	7
PE	16,5
EN 1852 requirement, un-notched	140

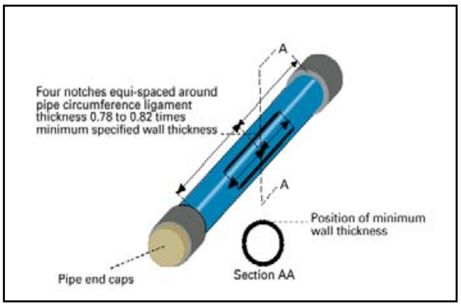

Figure 6. Notch resistance results and ISO13479 test sample.

Thermo-oxidative degradation

Results from thermo-oxidative degradation based on un-aged and 6 months and 12 months aged pipes in air/water at 95°C are seen in Figure 7.

Based on EN ISO 9080 (21) principles the results from 6 months and 12 months aged pipes should correspond to 50 and 100 years expected lifetime, respectively, at temperatures below 45°C. Therefore the remaining properties after ageing will indicate the residual operational life of the pipe.

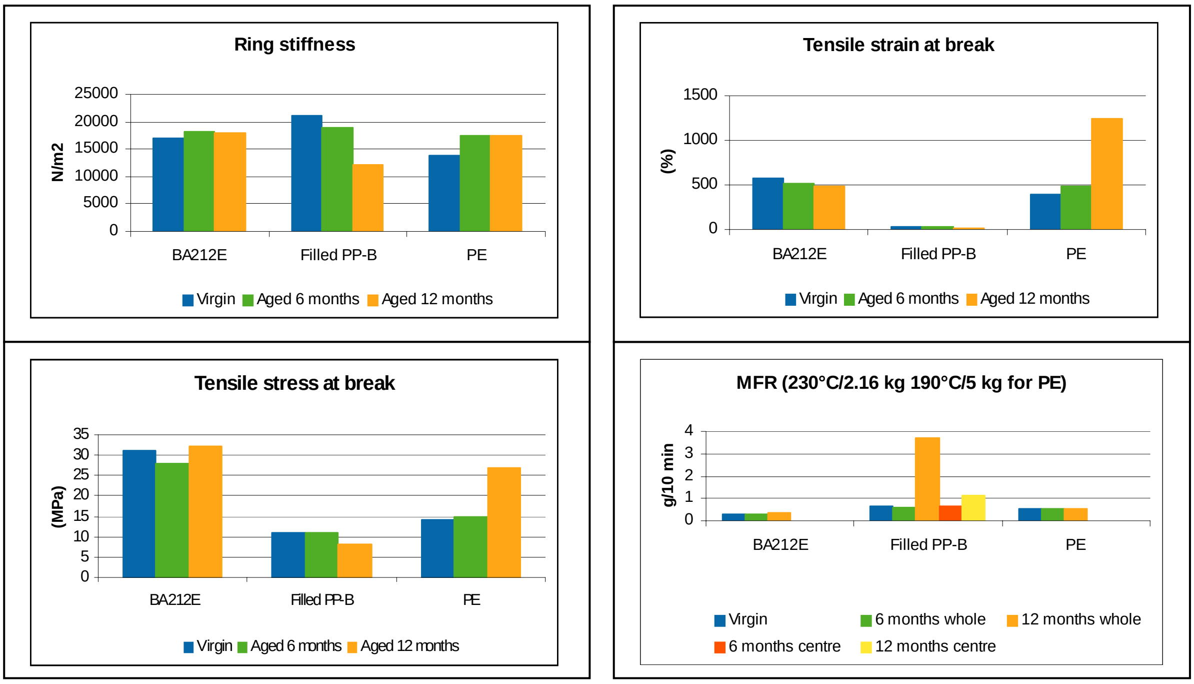

Figure 7. Mechanical properties on un-aged and aged pipes corresponding to >100 year lifetime.

In general, the reduction in properties (ring stiffness, tensile strain at break and tensile stress at break) are less than 25% after 12 months ageing in air/water at 95°C for the PP-HM pipe. For the HDPE material this is also the case but mainly based on the degradation mechanism giving higher values for ring stiffness and strain and stress at break after ageing. Only a minor change is also noted for MFR for both PP-HM and HDPE. Based on the thermo-oxidative degradation evaluation alone one may draw the conclusion that the HDPE material has sufficient properties for the application. However, based on the results from the other tests performed proves not to be the case.

For the mineral filled material a clear reduction is observed in the tensile strain at break and especially for the ring stiffness with aging, (i.e. there is a basic loss of the load bearing capability of the material. The large MFR increase from 0.64 to 3.7 g/10min is supporting this with samples taken from the full pipe wall. Based on samples taken from the centre of the pipe wall the increase was lower, from 0.64 to 1.16 g/min. This is also supporting the clear surface degradation in the “Janson” test samples as described above.

Environmental stress cracking, ESCR

Results from both ASTM D1693 (Bell) and ISO 13480 (Cone test) are shown below. The PE material shows a very low resistance to ESCR (cf. the PE80 requirement of > 7 days in ISO 13480), while excellent results are noted for the PP-HM material. The filled PP-B are still under test.

In the view of the high demands in operation with the stress cracking substances normally found in municipal sewage this could be considered as a relevant test.

Material	ASTM D1693 (hours to failure)	ISO 13480 (hours to failure)
PP-HM	>16.000 (interrupted)	>21 days (interrupted)
Filled PP-B		> 7 days (running)
HDPE	<70	<1 day

Computer simulation: Time dependent stresses in the pipe wall

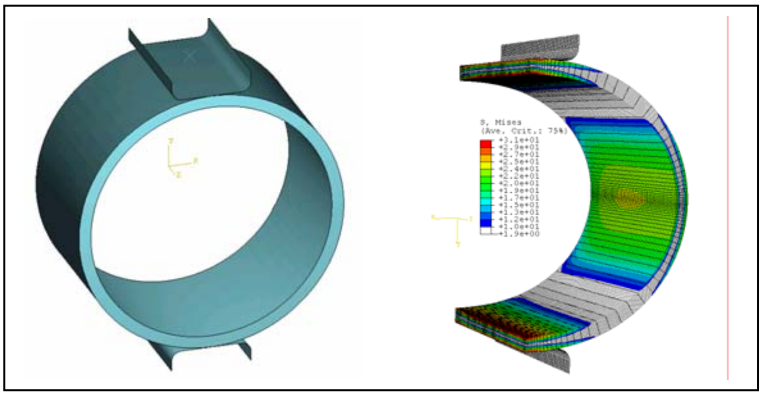

Figure 8. a) loading condition and b) PP-HM stress distribution at 15% deflection.

The stress distribution simulations have been carried out on the PP-HM and the HDPE material for up to 15 years operation. The principle loading conditions and stress distribution are shown in figure 8. In figure 9 a comparison of experimental results and calculated values for PP-HM and HDPE are given at 15% pipe deflection. In general, the stresses have decreased to around 20-25% of the original value after 8-10 years based both on the experimental results and the simulations performed. Also illustrated is the maximum von Mises stress distribution after 3 years for both HDPE and PP-HM at 15% pipe deflection. However considerable stresses remain in the pipe wall long after soil settlement, i e after 3 years the maximum stresses are around 9 MPa for PP-HM and 6 MPa for the HDPE material. Further work needs be done on corrugated pipe designs and at longer simulated times.

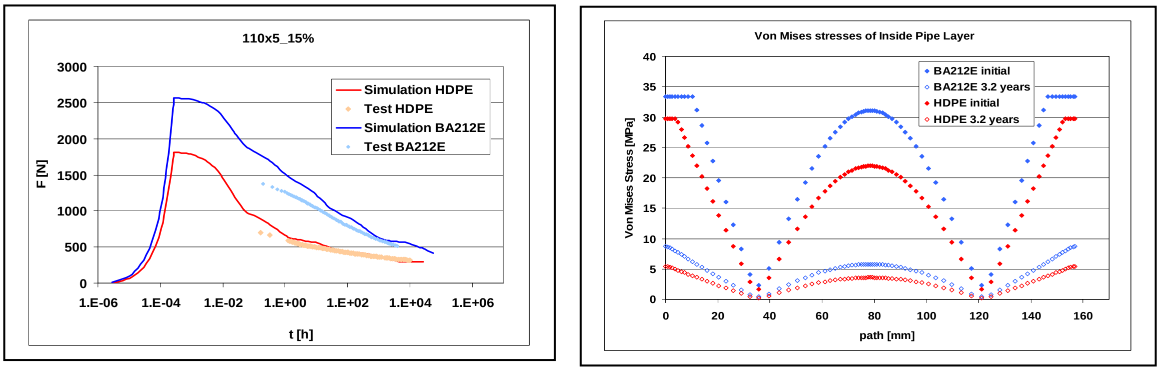

Figure 9. a) Comparison of calculated force vs log time and experimental data for the stress relaxation test of OD110 mm x 5 mm pipes at 15% deflection up to 15 years, b) von Mises stresses distribution at the pipe inner wall at 15% deflection showing initial stresses and stresses after 3.2 years.

CONCLUDING REMARKS

For the three materials tested under constant strain very different visual damage and failure mechanisms were observed:

i. For the HDPE material it has been clearly demonstrated that even under stress relaxation conditions the stress is sufficient to both initiate and propagate cracks through the pipe wall.
ii. For filled PP-B material the damage developed as an area of craze that did not penetrate the pipe wall, instead of the single crack brittle failure in the PE material.
iii. For PP-HM, the only damage observed was stress whitening.

A clear relationship between the deflection level and the time to failure was observed for the high modulus HDPE pipes, i.e. shorter failure times are found with higher deflection levels and after ageing. This opens up the possibility of estimating failure times similar to ISO 9080 principles for pressure pipes.

Although initially the HDPE compliance curves are linear at longer test time failures occur. Therefore for this material it is not possible to extrapolate according to the commonly referred hypothesis presented by Janson (8) and the high stiffness HDPE material is clearly unsuitable for use in pipes exposed to long-term deflection.

The filled PP-B was most severely affected by the ageing leading to considerable loss in load-bearing capacity as demonstrated by the ring stiffness, tensile strain at break and stress relaxation tests before and after ageing. For high deflection levels, this develops into non-uniform bending and hinge-forming, cf. figure 4.

No failures were seen for the PP-HM material for neither aged nor non-aged samples in the constant deflection tests up until 10.000 hours. No significant changes in material properties could be seen after ageing.

The CAED analysis confirmed that although the materials relax continuously, substantial stresses remain after 50 to 100 years of service. CAED will be a useful tool in evaluating the time dependent stresses in different structured wall pipe designs.

The testing methodology employed clearly differentiated between materials of different durability performance and highlighted important differences in the failure mechanisms. Therefore this could form the basis for evaluating durability and for defining performance requirements for 50 or 100 years life time. To confirm this concept further testing needs to be carried out on different materials and different pipe structures.

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