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Requirements for PE geopipes in German landfills with regard to stress cracking resistance and oxidation resistance

H. Zanzinger, SKZ - German Plastics Center, Würzburg, Germany

ABSTRACT
According to the European Landfill Directive, all components of the basal lining system in a landfill must fulfil their function over a very long period of time. The suitability of geopipes as part of the drainage system must be proven and their professional installation within the framework of quality management must be demonstrated. The SKZ/TÜV-LGA quality guideline (2017) represents here for the state of the art in Germany. PE geopipes must be made of PE 100 or PE 100-RC materials. PE 100-RC having higher resistance to slow crack growth are preferably be used in the basal lining systems. In Germany, a service life of 100 years is the requirement basis for permanent applications of drainage pipes as a function-determining element of the lining systems in landfills. Beside long-term hydrostatic strength ageing processes due to oxidation, media influences and temperature have to be considered. Therefore, proof of the ageing resistance to thermal oxidative degradation and to leaching of stabilizers must be provided by investigations in liquid media under oxygen pressure and elevated temperature in high-pressure autoclaves. Within the scope of quality monitoring, tests are carried out on PE moulding compounds, tests on solid walled and corrugated PE geopipes within the framework of factory production control and control tests on the construction site. Accelerated testing methods such as oxidation resistance testing with high-pressure autoclaves and stress crack resistance testing with the strain-hardening method play an important part in this.

1. INTRODUCTION

According to the German Landfill Ordinance (DepV), all components of the barrier system must fulfil their function over a period of at least 100 years. Their suitability must be proven to the responsible authority. For the assessment of the suitability of PE geopipes for landfills, the countries define test criteria and specify requirements for professional installation and quality management in nationwide quality standards. The interaction between PE geopipes and coarse stone backfill (Brachman et al., 1998) and their behaviour under loads of up to 1200 kPa (Zanzinger and Gartung, 1998) together with studies on the durability of these drainage pipes after several years in service have been investigated by several researchers. At several landfill sites in Germany damaged and broken geopipes were found (Zanzinger et al, 2014). Cracks have been detected. There are many speculations about the possible reasons of these failures but one seems to be clear. The geopipes used must be made from a highly stabilized and stress crack resistant material in order to ensure a very long service life under extreme conditions like extremely high loads, elevated temperatures and a harsh environment embedded in coarse gravel in a landfill basal lining system. The experience of decades in the use of PE geopipes in a leachate collection system in landfills made it necessary to define very detailed the specific requirements on the materials used for the production of PE geopipes that they can last for centuries in a basal lining system of a modern landfill. As a conclusion new requirements on the PE material have been developed. The SKZ/TÜV-LGA quality guideline (2017) represents the nationwide standard in Germany (Federal Uniform Quality Standard BQS 8-1 "Pipes, Manholes, Components"). Drainage pipes manufactured, tested and installed in accordance with the SKZ/TÜV-LGA quality guideline (2017) thus meet the requirements of the state of the art in Germany. Their suitability must therefore be proven on the basis of this standard.

2. POLYETHYLEN (PE)

Drainage geopipes for German landfills must be made of PE 100 or PE 100-RC materials. PE 100-RC materials have a much higher resistance (around 30 times) to slow crack growth in Full Notch Creep Tests (FNCT) acc. to ISO 16770 than PE 100 materials. PE 100-RC should therefore preferably be used in the basal lining system.

For permanent applications of PE drainage geopipes as a function-determining element especially of the basal lining systems in landfills, a service life of 100 years for permanent temperatures up to 40°C is the requirement criteria. These parameters are determined by testing the creep rupture internal pressure strength. The extrapolation for the design life and temperature must be carried out in accordance with EN ISO 9080.

Polyolefins are also subject to ageing processes due to oxidation, media influences and temperature. Therefore, supplementary proof of the ageing resistance to thermal oxidative degradation and to the leaching of stabilizers must be provided by investigations in liquid media using accelerated ageing tests under oxygen pressure and elevated temperature in high-pressure autoclaves. Martin & Zanzinger (2018) have presented current results of investigations of PE geopipes with high thermo-oxidative resistance for applications at higher temperatures and long service lives. The detection method is described in the SKZ house guideline HR 10.01 (2018) "Pipes made of polyethylene, PE 100-(RC)Ox with high thermo-oxidative resistance for applications at higher temperatures and long service lives - Technical requirements and testing".

3. SKZ HR 10.01

The testing and monitoring specification SKZ HR 10.01 defines the testing, approval and monitoring procedure, for example for drainage geopipes in the basal lining system, and serves as a supplement to the existing series of standards and directives.

SKZ HR 10.01 defines properties, requirements and test methods for PE 100-RCOx geopipes. The addition "Ox" in the designation stands for high thermo-oxidative resistance. Further requirements are defined which go beyond the minimum requirements of the relevant standards and specifications for geopipes made of PE 100-RC. This applies in particular to the choice of raw materials for stabilization. The stabilization is tested indirectly with the oxidation induction time (OIT) acc. to EN ISO 11357-6.

4. PE 100-RCOX

4.1 Tests on PE materials

SKZ HR 10.01 applies to pipes made of polyethylene under a continuous operation temperature of 40°C. With regard to the area of application, the resistance of the material used to the leachate to be discharged must be checked. The requirements are summarized in Tables 1 and 2.

Table 1: Basic requirements for the material PE 100

Property	Test method	Requirements
Density	EN ISO 1183-1	≥ 945 kg/m³
Melt mass flow rate (MFR 190/5)	EN ISO 1133-1	(0.15 to 1.5) g/10 min
Carbon black dispersion	ISO 18553	≤ Grade 3, dispersion class A1, A2, A3, B
Carbon black content	EN ISO 11358-1	(1.8 to 2.5)%

Table 2. Additional requirements for the material PE 100-RC

Property	Test method	Requirements
Failure time in Full-Notch-Creep-Test (FNCT)	ISO 16770 (80°C, 4 MPa, 2% Arkopal N-100)	≥ 8760 h
Strain hardening modulus (alternative to FNCT)	ISO 18488	≥ 50 MPa
Failure time in point load test (on solid wall pipe)	PAS 1075 (80°C, 4 MPa, 2% Arkopal N-100)	≥ 8760 h
Notch test (on solid wall pipe)	EN ISO 13479	≥ 8760 h
Heat aging with flow	PAS 1075	> 100 years at 20 °C w/o rupture
Oxidation induction time (OIT)	EN ISO 11357-6	≥ 40 min at 210 °C
Heat aging with flow	PAS 1075	> 8760 h

4.2 Test program for high-pressure autoclaves tests on PE 100-RCOx materials

High-pressure autoclave tests (HPAT) are carried out to determine the resistance of PE 100-RCOx materials to thermo-oxidative degradation. The ageing test follows the methodology according to ISO 13438:2004, method C. In the test program described here, the storage is continued until a pre-defined failure criterion is passed. The aim is to deduce a service life of 100 years at 40 °C continuous temperature from the failure times at elevated temperatures and elevated oxygen pressures.

PE 100-RCOx granulates are - by injection moulding or pressing of plates - used to form type 2 test specimens according to EN ISO 6259-3 with a thickness of 4 mm. These are stored in high-pressure autoclaves under the following test conditions: at 90°C / 50 bar O_2, at 90°C / 5 bar O_2, at 90°C / 1.5 bar O_2, at 80°C / 50 bar O_2 and at 70°C / 50 bar O_2.

After certain time intervals, the elongation at break is determined acc. to EN ISO 6259-3 and the OIT-value acc. to EN ISO 11357-6. In addition, the oxygen pressure is continuously recorded.

One criterion for failure under test conditions is the achievement of 50% residual elongation at break. The "onset point" of the oxygen pressure drop can be used as an additional indicator for the end of the test period. The oxygen pressure drop occurs when the polymer oxidizes and oxygen is consumed. Furthermore, the application of the OIT-value over the test period offers a possibility to estimate the point in time at which the polymer is no longer stabilized by antioxidants. This happens after the OIT-value has almost reached zero.

A 3D-extrapolation (Figure1) is performed to estimate the service life under application conditions, e.g. 40 °C and 0.21 bar O_2. For this purpose, the failure times determined under test conditions are displayed in an Arrhenius-typical application of the inverse temperature (1/T) over the logarithmic time (ln t) and over the amount of oxygen dissolved in the aqueous medium (ln c(O_2)). The extrapolation to the application condition: 40 °C continuous temperature and 0.21 bar O_2 (corresponds to 6.9 mg/l at 40 °C) is carried out here using Equation 1:

$$t = A \cdot e^{\frac{B}{T}} \cdot c^{D} \qquad [1]$$

with: t failure time; A, B, C and D constants; T absolute temperature; c concentration of oxygen dissolved in the medium.

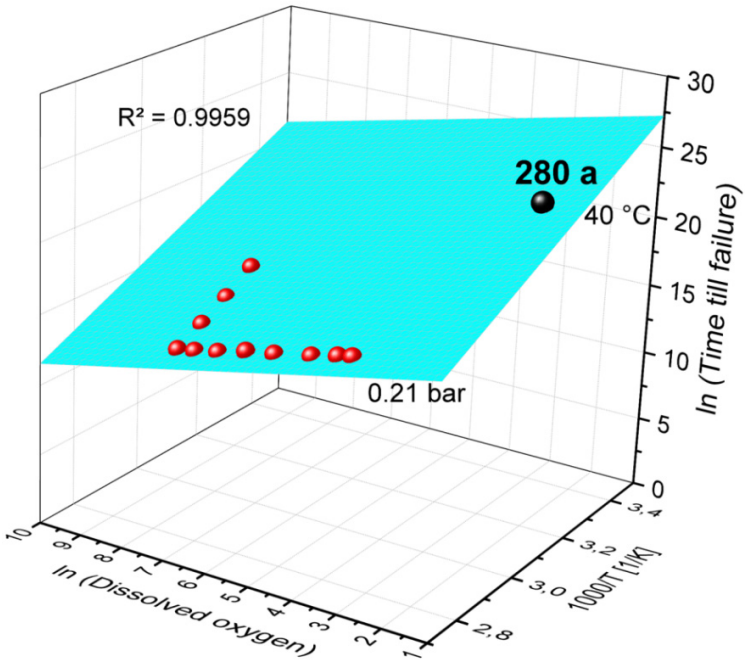

Figure 1. Example of a 3D-extrapolation of a HPAT in an Arrhenius-typical application of the inverse temperature (1/T) over the logarithmic time (ln t) and over the amount of oxygen dissolved in the aqueous medium (ln c(O_2)).

Note: The concentration of oxygen dissolved in the medium depends on oxygen partial pressure and temperature (Geng & Duan, 2010).

The tested PE material in Figure 1 has passed the requirement as the estimated service life was found to be ≥ 280 years at 40 °C application temperature and atmospheric pressure (= 0.21 bar oxygen partial pressure).

5. LEACHATE DRAINAGE PIPES

5.1 Tests on PE geopipes

Leachate drainage pipes in Germany must comply with DIN 4266-1. Solid wall PE geopipes in acc. with DIN 8074 / DIN 8075 or PE geopipes with corrugated walls and smooth inner surfaces in acc. with DIN 16961-1 and -2 must be used.

Acc. to DIN 19667 and DIN 4266-1, the minimum internal diameter is 250 mm. When selecting the geopipe, the calculated deflection must be taken into account for the inside diameter. For inspection reasons, an inner diameter of approx. 300 mm is recommended for new installations. Inspections and their evaluation can be optimized by a light-coloured inner pipe surface.

At least 100 cm²/m of water inlet area must be provided for collecting landfill leachate. The perforation above the support (usually 2/3 perforated) can be perforated or slotted. Their geometry must be matched to the grain size of the drainage gravel material. The hole aperture acc. to DIN 4266-1 should be at least 12 mm in diameter, the minimum slot width should not be less than 10 mm. Slot corners should be rounded to a radius of half the slot width and should be free of burrs. In order to avoid water accumulation in the geopipe bearing area, the lower water inlet openings for pipes from SDR 17 (Standard Dimension Ratio) must be inclined at an angle of 0°to 5° to the pipe bottom.

Pipe joints can be designed as welded joints or sliding sockets. The pipes must be joined by butt fusion, electro fusion or, in special cases, hot gas extrusion welding. DVS guidelines 2207 and 2208 must be observed. For the selected type of connection, the same bottom must be guaranteed. In the case of connections by means of heated element butt welding, the shape of the inner weld beads must allow camera inspection and flushing. In the case of butt welded pipes with weld bead dimensions > 10 mm, the inner beads must be removed. Contrary to DIN 19667, external beads only need to be removed if there is no indentation in the geopipe bearing area in order to accommodate them. External beads must always be removed from geopipes installed using the burst lining method. If bends are required in the pipe run, they must be designed in such a way that camera inspection and flushing are possible (e.g. version with suitable radius and free of internal beads). The requirements for PE 100 resp. PE 100-RC are shown on Tables 3 and 4.

Table 3. Basic requirements for PE 100 pipes

Property	Test method	Requirements
Texture, colour	Visual inspection	EN 12201-2
Geometry	EN ISO 3126	EN 12201-2, section 6
Longitudinal shrinkage	EN ISO 2505	EN 12201-2, section 8.2 - Tab. 5
Creep rupture internal compressive strength	EN ISO 1167-1, -2	σ = 12.4 MPa for 100 h at 20°C σ = 5.4 MPa for 165 h at 80°C σ = 5.0 MPa for 1000 h at 80°C
Resistance to slow crack growth	EN ISO 13479	80°C, 9.2 bar, 500 h (EN 12201-1, section 4.4.2)
Homogeneity	Microtome slices ISO 18553	Method A: inhomogeneity ≤ 0.02 mm^2 Method B: pigment dispersions ≤ grade 3
MFR 190/5	EN ISO 1133-1	MFR value max. ± 20% change
Elongation at break	EN ISO 6259-1, -3	EN 12201-2, Tab. 3

Table 4. Additional requirements for PE 100-RC pipes

Property	Test method	Requirements
Failure time in the FNCT	ISO 16770 (80°C, 4 MPa, 2% Arkopal N-100), in MD	≥ 3300 h (PAS 1075)
Strain hardening module (alternative to FNCT)	ISO 18488 in MD	≥ 50 MPa (-10%)
Failure time in point load test	PAS 1075 (80°C, 4 MPa, 2% Arkopal N-100) pipe dimension: DN 110 SDR 11	≥ 8760 h (PAS 1075)
Penetration test	PAS 1075, Annex A4 (9000 h)	≥ 50% residual wall thickness (PAS 1075)
OIT	EN ISO 11357-6	≥ 40 min at 210 °C

5.2 High-pressure autoclave testing of PE 100-RCOx geopipes

For the inspection of PE geopipes manufactured from materials certified acc. to SKZ HR 10.01, the PE geopipe is checked for thermo-oxidative resistance in the "one-point" HPAT.

Type 2 test specimens acc. to EN ISO 6259-3 are milled out of a geopipe section with sufficiently large pipe wall thickness in the extrusion direction from the centre of the pipe wall. These are subjected to an HPAT acc. to ISO 13438:2004 at 90 °C continuous temperature and 5 bar O_2. After a specified test period for the certified material, the residual elongation at break must be at least 50%.

The requirement for the test time, at which the residual elongation at break must be > 50%, is determined by the pressure and temperature dependence of the raw material. The dependencies of pressure and temperature were determined on the material during the HPAT test. These results are used to calculate the requirement (acceptable failure time at 90 °C and 5 bar O_2) for the specimens taken from the geopipe:
The level obtained by comprehensive HPAT on the material (application of the inverse absolute temperature (1/T) over the logarithmic time (ln t) and over the amount of oxygen dissolved in the aqueous medium (ln c(O_2)), usually does not run through the point at 100 years' service life at 40 °C and 0.21 bar oxygen partial pressure (corresponds to 6.9 mg/l). For thermo-oxidatively more resistant materials, the level cuts the time axis for longer times under application conditions. This plane must be shifted along the time axis so that it runs through t = 100 years.

The minimum test time on the geopipe sample must be calculated at 90 °C and 5 bar oxygen overpressure (corresponds to 140 mg/l). It corresponds to the calculated minimum testing time on the material. Experience has shown that this test duration ranges from 1 to 2 months. After reaching the required test time, 5 specimens are removed and tested in a tensile test acc. to EN ISO 6259-3. The residual elongation at break must be > 50%.

6. QUALITY ASSURANCE

The SKZ/TÜV-LGA quality guideline (2017) requires that both the manufacturers of the materials and the manufacturers of the PE geopipes must have their own factory production control (FPC) and independent external quality assurance (QA). The FPC shall be reviewed regularly by the QA. Sampling and testing are the responsibility of the third-party supervisor.

The type and scope of the tests on the compounds and the PE geopipes required under the FPC are listed in Tables 5 to 7.

Table 5. Tests on the PE Moulding Compound as Incoming Inspection

Property	Test method	Requirements
Density	EN ISO 1183-1	≥ 945 kg/m³
Melt mass flow rate (MFR 190/5)	EN ISO 1133-1	(0,2 - 0,4) g/10min (PE 100-RC) (0,2 - 1,4) g/10min
Oxidation induction time (OIT at 210 °C)	EN ISO 11357-6	≥ 40 min (PE 100-RC)
Carbon black dispersion	ISO 18553	Dispersion class A1, A2, A3, B
Carbon black content	EN ISO 11358-1	(2.0 to 2.5)%
Full Notch Creep Test (FNCT)	ISO 16770	t_{FNCT} ≥ 8760 h (PE 100-RC)
AFNCT (alternative to FNCT)	ISO 16770	t_{AFNCT} ≥ 200 h (PE 100-RC)
SHT - Strain Hardening Module (alternative to FNCT)	ISO 18488	≥ 50 MPa

Table 6. Tests on solid wall PE geopipes (DIN 8074 / DIN 8075) within the scope of the FPC

Property	Test method	Requirements
Creep rupture internal pressure behaviour at 80°C,165h and at 80°C, 1000h	EN ISO 1167-1	no break
FNCT (in MD)	ISO 16770	t_{FNCT} ≥ 3300 h (PE 100-RC)
AFNCT (in MD) (alternative to FNCT)	ISO 16770	t_{AFNCT} ≥ 180 h (PE 100-RC)
SHT (in MD) (alternative to FNCT)	ISO 18488	≥ 45 MPa (PE 100-RC)
MFR 190/5	EN ISO 1133-1	Raw material value ± 20%
OIT at 210°C in centre of pipe wall	EN ISO 11357-6	≥ 40 min (PE 100-RC)
Density	EN ISO 1183-1	≥ 945 kg/m³

Table 7. Tests on corrugated PE geopipes with a smooth inner pipe surface (DIN 16961) within the scope of the FPC

Property	Test method	Requirements
MFR, properties, surface properties, colour, dimensions, weldability, ring stiffness	DIN 16961-2	DIN 16961-2
SHT (in MD)	ISO 18488	≥ 45 MPa
OIT at 210 °C (from supporting pipe wall)	EN ISO 11357-6	≥ 40 min (PE 100-RC)

All test methods for stress crack resistance so far refer exclusively to tests to be performed on specimens taken from plates. These are pressed from the molten PE moulding compound (granulate) under pressure into the shape of a plate.

Strictly speaking, there is no standard test procedure for the stress crack resistance tests on extruded pipes. However, the SKZ/TÜV-LGA quality guideline (2017) stipulates that the respective test specimens are to be taken from the centre of the pipe wall in the axial direction of the geopipe. The specimens are milled into the required shape in order to carry out the test on them. Of course, the manufacturing process of the respective extrusion process and the production speeds and all manufacturing parameters as well as the cooling and the resulting residual stresses in the geopipe have an influence on the results. On the other hand, it can also be seen that the plate pressing process can also effect the results.

Our experience has shown that the variations in the results on PE geopipes are comparable to the variations on pressed plates. Nevertheless, in the SKZ/TÜV-LGA quality guideline (2017), the requirements for the PE geopipes for these tests have always been set lower than the requirements for the moulding compounds themselves.

In addition, the PE geopipes are subject to an external construction quality assurance (CQA) on site. The welded joints in particular are inspected and tested here. The type, scope and frequency of the common tests on the PE geopipes required within the scope of CQA are listed in Table 8.

Landfill leachate drainage geopipes made of PE 100-RC so far could not be tested for stress crack resistance within the scope of CQA, because no rapid, universally accessible test method was available. Now, however, three alternative test methods may be used as equivalent evidence. In the case of corrugated PE geopipes, however, only the strain-hardening test can be used, because the wall thicknesses do not permit bigger specimens.

Table 8. Tests on PE geopipes within the scope of the CQA

Property	Test method	Requirements
MFR 190/5	EN ISO 1133-1	raw material value ±20%
Density	EN ISO 1183-1	≥ 945 kg/m³
OIT at 210 °C	EN ISO 11357-6	≥ 40 min (PE 100-RC)
AFNCT (PE 100-RC in MD)	ISO 16770	$t_{AFNCT} \geq 180$ h
SHT (alternative to AFNCT)	ISO 18488	≥ 45 MPa
Technological bending test on the butt joint of HS specimens[1]	DVS 2203-5	./.
alternative: Tensile test on butt joint of HS specimens[1]	DVS 2203-2	./.
Evaluate defects of HS welds[1]	DVS 2202 appendix 1	evaluation category 1
Technological bending test on the butt joint of WE specimens [2]	DVS 2203-5	./.
alternative: Tensile test on butt joint of WE specimens [2]	DVS 2203-2	./.
Evaluation of faults in WE welds [2]	DVS 2202 appendix 5	evaluation category 1
Torsion shear and radial shear test of HM specimens [3]	DVS 2203-6 appendix 1	DVS 2203-1 appendix 4
alternative: Linear shear test of HM specimens [3]	DVS 2203-6 appendix 1	./.
Evaluation of defects of HM welded joints [3]	DVS 2202 appendix 2	evaluation category 1

[1] Heating element butt welding (HS), [2] hot gas extrusion welding (WE), [3] electro fusion welding (HM)

7. CONCLUSIONS

After several years in service in landfills, a number of PE geopipes were examined. It was found that they have exhausted part of their service life and some have already failed. At a service operating temperature of > 40 °C it is extremely doubtful whether these old PE geopipes reach a residual service life of many decades. They have an important task in a landfill basal lining system. As a conclusion high-stabilized and stress crack resistant material must be used in order to ensure a very long service life under extreme conditions.

The state of the art for new landfill leachate drainage PE geopipes to be installed in Germany has been summarised. New requirements for the moulding compounds and for the PE geopipes were specified. Requirements for the

verification of the service life of 100 years at 40 °C were given. Two new test methods (AFNCT and SHT) have been included for quick testing and verification of stress crack resistance of the raw materials and the PE geopipes as well.

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