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STATUS ASSESSMENTS OF DISTRICT HEATING PIPES

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ABSTRACT

Large parts of the existing pre-fabricated district heating pipe networks are close to reaching their technical life. There is a need to assess the status of the district heating pipes in order to plan maintenance and replacements of pipes. A first step towards developing a simple and cheap method for technical status assessments of existing pipes without shutting the pipes down has been taken.

The proposed mechanical field method is based on that the district heating pipes are uncovered and cylindrical samples still attached to the service pipes are created by removing material around them by use of hole drills. Laboratory equipment for pulling or turning the cylindrical samples off, while measuring load and deformation, has been developed.

INTRODUCTION

The aim with this work is to take a first step towards developing a simple and cheap method for technical status assessments of existing pipes without shutting the pipes down has been taken. The method can be a foundation for estimation technical or economical life of the district heating pipe. The economic life has come to an end when it is estimated that it is profitable to replace the pipe instead of continuing to use it.

The work is focused on pre-fabricated district heating pipes with a service pipe of steel, insulation of polyurethane and a casing pipe of polyethylene.

Modernisation of the pipelines is a top priority in order to enhance the efficiency of the distribution systems according to the technology platform DHC+[1]. In Sweden, approximately 16 000 km of pipeline are installed, with an average construction cost of 500 €/m. In order for the current replacement rate of 50 km per year to be feasible, an expected technical life of 320 years would be required, while in reality, pre-insulated bonded pipes of current standard may last for 30 – 70 years. This pipe type has dominated the market since the early 80's, and one might therefore expect that the need for replacement will increase with five to ten times the coming years. For Swedish conditions, this means that maintenance of the existing grid will require largely the same investment volume as new construction.

Extensive laboratory tests and field studies have carried out in Germany on ageing of pre-fabricated district heating pipes, see References [2], [3] & [4]. It was established that ageing of the polyurethane (PUR) foam does not follow the time/temperature relation in the EN 253 product standard, which is based on Nolte's experiments [5] of ageing of polyurethane in an oxygen free environment. This discrepancy is likely due to oxidative degradation of the foam, see also References [6] & [7]. The significance of this phenomenon with respect to long term strength and thermal insulation capacity remains to be clarified. This work is also publish as an internal report

DEFINITION OF TECHNICAL LIFE

It is not motivated to define the technical life based on a standard requirement on the axial shear strength of 0.12 MPa in EN 253, since the pipe will not be subjected to such large shear stresses between the service pipe and the polyurethane foam. Based on the standard EN 13941, the shear stress between service pipe and the polyurethane has been calculated for a few cases. The shear stress is based on the linear built up of the fix force along the friction length. For some cases extreme cases the shear stress reaches about one third of the requirement 0.12 MPa.

Instead, it is suggested that the definition of life is based on a reduced value. The technical life of a pipe can be estimated based on the measured axial shear strength, an assumed yearly reduction of the axial shear strength at the specific service temperature of the pipe and a life criterion based on the smallest allowable axial shear strength.

Table 1: Calculation results of shear stress by use of EN 13941. Weight density of soil 18 kN/m^3, lateral soil coefficient 0.5, service pressure 16 bar, Young's modulus 210 GPa, Poisson's ratio 0.3 and thermal expansion 11 10^{-6} K^{-1} of steel have been used.

Dimension	Temperature [K]	Friction [-]	Cover [mm]	Shear stress [kPa]
DN 100/225	160	0.6	2000	32
DN 100/225	90	0.6	2000	32
DN 100/225	160	0.4	600	6.9
DN 100/200	160	0.6	2000	29
DN 100/250	160	0.6	600	36
DN 65/160	160	0.6	2000	35
DN 65/160	160	0.4	600	7.3

AGEING OF DISTRICT HEATING PIPES

There are different ways for accelerated aging of polyurethane foam. Either can the polyurethane foam be aged out- or inside a container. The container can be a district heating pipe or have some other shape. Here, we have chosen to use accelerated ageing of district heating pipes in the laboratory and pipes which have been in service.

Accelerated ageing of pipes in the laboratory

The temperature field should also be chosen. Here, we have heated the service pipe to 160°C and outside casing it is room temperature. For the polyurethane in a pipe in service the temperature field will be similar, but the boundary conditions differ.

Accelerated ageing in the laboratory is motivated by the fact that the temperature load is known. It is the foam close to the service pipe that will age fast due to thermal degradation. For the activation energy 150 kJ/mol, the Arrhenius equation gives 70 times faster ageing at 160°C than 120°C, and 180 times faster at 160°C than 80°C.

However, the diffusion of oxygen through casing will not increase that much compared to the situation in service. Suppose that the temperature of the casing is increased from 15°C in service to 30°C in the laboratory, diffusion rate will be twice as high for the activation energy 35 kJ/mol.

In the investigations two district heating pipes of dimension DN 100/225 and type Contipipe manufactured by LOGSTOR have been used. The pipes had no diffusion barrier. However, the production process had to be interrupted before these pipes were manufactured and the bonding between the service pipe and the polyurethane was not as good as it should have been. Good bonding was only verified for about half of the circumference.

In the investigations a non-aged pipe, and pipes aged 1800 h, 3600 h and 5400 h were used. The pipes were aged standing by use of circulated heated oil.

Pipes from service

A few pipes, which have been in service and aged naturally, have also been investigated, see Table 2. The blowing agent is Freon 11 (CFC 11) in all the pipe but the newest, where cyclopenthane was used.

Table 2: Investigated district heating pipes from service.

Notation	Installation	Dimension	Blowing agent	Temperature	Flow / Return
GA	1986	DN40/125	CFC11	75-100	F
GBF	1987	DN300/500	CFC11	75-100	F
GBR	1987	DN300/500	CFC11	40-70	R
GCF	1991	DN250/450	CFC11	70-105	F
GCR	1991	DN250/450	CFC11	40-60	R
GDR	2007	DN200/355	CP	40-60	R

MECHANICAL TESTING

Two kinds of mechanical tests have been carried out. First, standard tests characterizing the change of axial shear strength and the change of compressive strength due to ageing have been done. Second, tests in order to develop a simple mechanical field method have been carried out.

Axial shear strength

The tests of the axial shear strength have been carried out in room temperature as described in EN 253 with test object of length 200 mm.

The axial shear strength is

$$\tau_{ax} = F_{ax}/(\pi D_s L) \qquad (1)$$

where

F_{ax} = measured axial force [N]
D_s = outside diameter of service pipe [mm]
L = length of test object [mm]

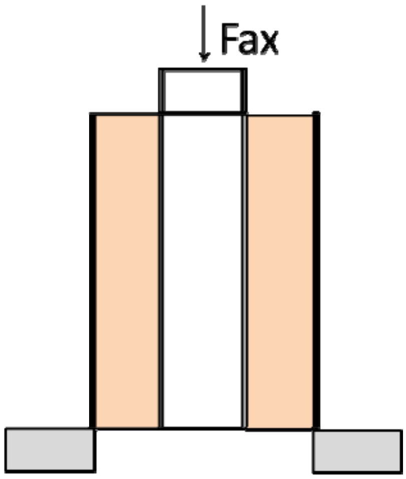

Figure 1: Sketch of axial shear strength test.

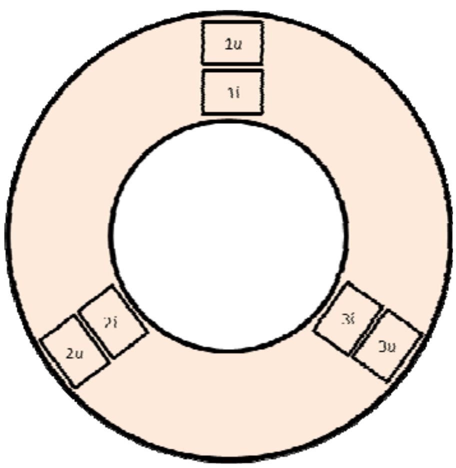

Figure 2: Sketch of positions of test specimens for compressive strength.

Compressive strength

The tests of the compressive strength have been carried out in room temperature as described in EN 253. In order to investigate the influence of the temperature, test specimens have been taken both close to the service pipe and far away from it, see Figure 2. The specimens have been collected within a length of 180 mm along the pipe. The size of the test specimens before testing is 30x30x20 mm. The compressive strength is the stress at 10% compressive strain in the radial direction.

DEVELOPMENT OF MECHANICAL FIELD METHOD

The purpose of the work is to develop a simple and cheap mechanical field method for technical status assessment of existing pipes without shutting the pipes down.

Based on two ideas, two methods have been tested for characterizing the bonding between the polyurethane and the service pipe. In both methods cylindrical test specimens still bonded to the service pipe are uncovered, see Figure 3. Two hole drills were used for shaping the test specimens: a larger with an outside diameter of 38 mm and a smaller with an inside diameter of 27 mm. In the methods, the test specimens have been either pulled or turned loose from the service pipe. Aluminium pipe holders with an inside diameter of 27 mm are attached to the test specimens by use of glue, see Figure 4.

Pulling specimens loose

A tensile testing machine was used for pulling the cylindrical test specimens of polyurethane loose. In most tests the feeding speed was 0.5 mm/minute.

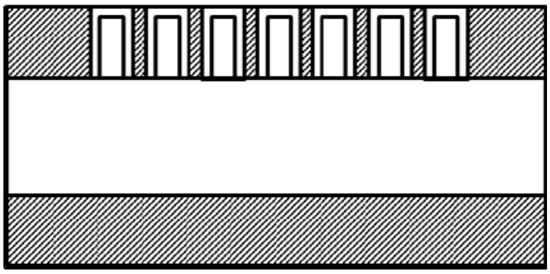

Figure 3: District heating pipe with uncovered cylindrical test specimens still attached to the service pipe.

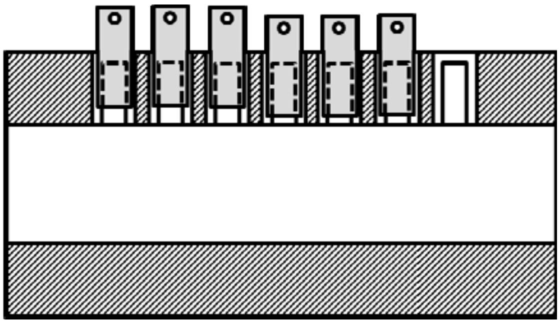

Figure 4: District heating pipe with cylindrical test specimens on to which aluminium pipes holders have been fixed by use of glue.

Figure 5: Picture of laboratory equipment for pulling cylindrical specimens loose.

Figure 6: Picture of laboratory equipment for turning cylindrical specimens loose.

Turning specimens loose

A rig for turning cylindrical specimens of polyurethane loose, while measuring the applied torque and the rotation of the holder, has been manufactured, see Figure 6. The rig has a piece of plastic material mounted on an aluminium bar with seven cylindrical holes. The size of the holes is adjusted to fit the aluminium pipes. The holes are located just above the cylindrical test specimens of polyurethane.

The holes in the plastic material can be used as bearings useful for precise drilling of specimens, guidance while gluing aluminium pipe holders and carrying out the tests while turning the specimens loose.

The tests are carried out manually by hand, while the applied torque and the turning angle are measured. A static torque transducer located below the bearing is used for measuring the torque needed for turning the test specimen loose. The frictional torque at the bearing is hereby eliminated. A wire potentiometer and a wheel are used for measuring the rotation of the holder.

CELL GAS ANALYSIS

The partial pressures of the gases p_i [Pa] in the cells of the foams were determined according to a method thoroughly described in Reference [9]. Foam sample cylinders (diameter about 21 mm, length 40-60 mm) were ground in a closed system. This system was flushed with dinitrogen oxide for removing all air surrounding the sample, but also for making it possible to determine the true volume of the sample. The outer cell layer will always be more or less damaged during sampling, which makes it impossible to determine the true volume of the sample only by using a slide calliper. After flushing the sample was ground into powder. The released cell gas was collected in a glass syringe and the syringe volume was determined. The content of the released gas was analysed by use of a gas chromatography, which was equipped with a thermal conductivity detector. The concentration of each gas x_i [% of volume] in the cell gas was determined and the total cell gas pressure P_{tot} [Pa] was calculated. The small volume of dinitrogen oxide penetrating the foam during flushing was considered, when calculating P_{tot}. The partial pressures of the cell gases were calculated as

$$p_i = x_i \cdot P_{tot} \qquad (2)$$

RESULTS OF STANDARD MECHANICAL TESTS

The axial shear strength has been measured for non-aged pipes, and accelerated aged pipes. The requirement on the shear strength in EN 253 is 0.12 MPa. The shear strength is in principle decreasing with ageing time. A pipe from service in 25 years has also been investigated. The latter pipe has been manufactured with a blowing agent CFC11 and is still in good shape.

The compressive strength of the polyurethane foam has been measured for non-aged pipes, and accelerated aged pipes. The requirement on the compressive strength in EN 253 is 300 kPa. The compressive strength is increasing with ageing time. Too few samples have been tested for verifying that the compressive strength is lower for the specimens taken closer to the service pipe. The hardening process continues before the degradation process of the foam has a large influence. A pipe from service in 25 years has also been investigated and the compressive strength was found to still be satisfying.

RESULTS OF MECHANICAL FIELD METHOD

Ultimate tensile stresses for the pulling method are shown in Figure 9. Often, in the tests with longer specimens the fracture occurred far from the service pipe. Fracture also occurred inside the aluminium holder, when the glue had moved during appliance of the holders. For testing the foam close to the service pipe the length of the specimens was decreased. However, fracture still occurred inside the aluminium holder. The foam becomes more brittle and stiffer after ageing. Since the bonding varied around the circumference, the test specimens were taken along a generatrix, where the bonding was considered as good.

Ultimate shear stresses for the turning method are shown in Figure 10. When longer test specimens were used, fracture occurred perpendicular to the principal stress direction pertaining to tension. At the periphery the maximum shear stress is as large as the tensile principal stress. For elimination tensile fracture, shorter test specimens were used in the following investigations. For the shorter test specimens the fracture was initiated in the foam at the service pipe, see Figure 11. Also here, the specimens were taken along a generatrix, where the bonding was considered as good.

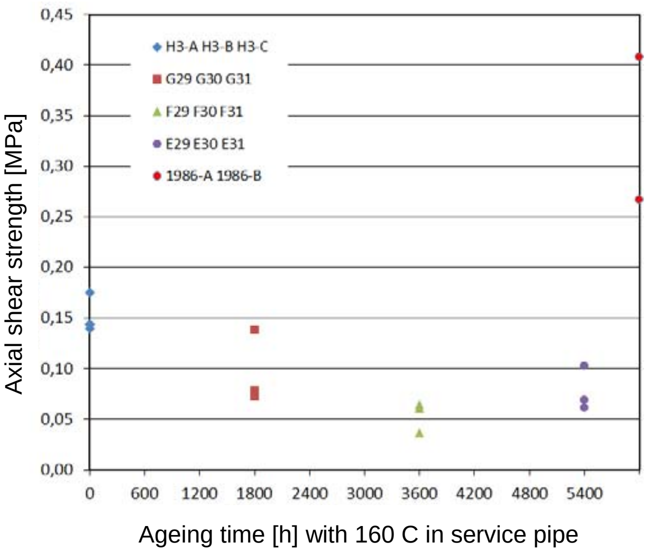

Figure 7: Axial shear strength of accelerated aged district heating pipes and a pipe GA which have been in service in 25 years.

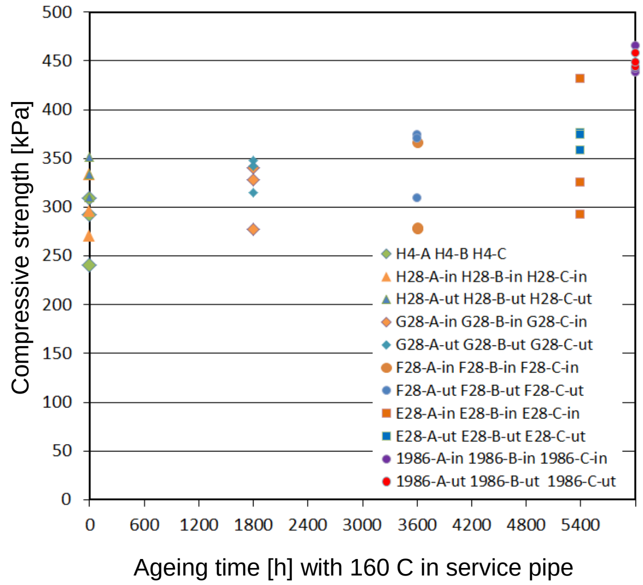

Figure 8: Compressive strength of accelerated aged district heating pipes and a pipe GA which have been in service in 25 years.

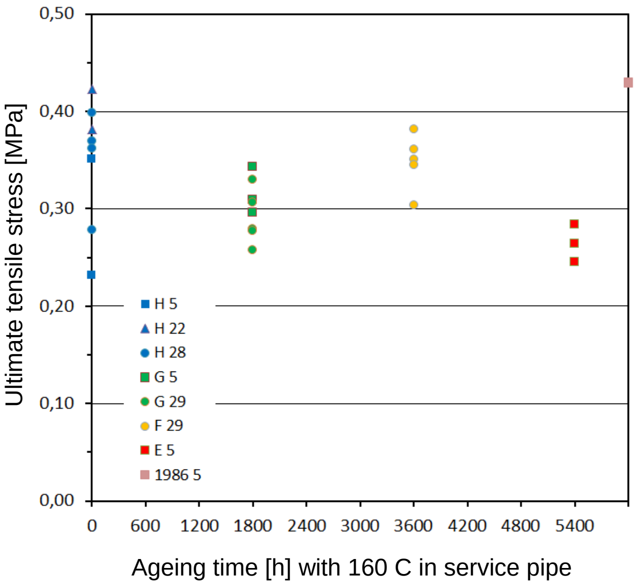

Figure 9: Measured ultimate tensile stress of test specimens as function of ageing time in laboratory and also for a pipe GA which have been in service for 25 years. Length of specimen is part of notation.

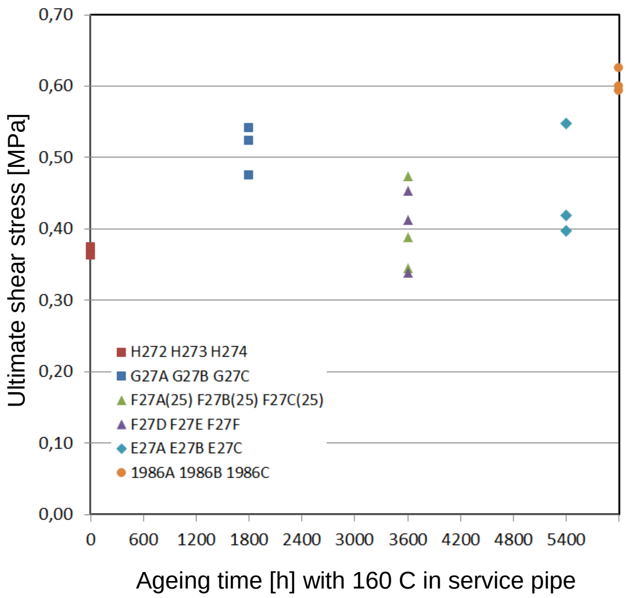

Figure 10: Measured ultimate shear stress of test specimens as function of ageing time in laboratory and also for pipe GA which have been in service for 25 years. For 3600 h, results for specimens of both length 25 mm and 5 mm are given.

Discussion about development of field method

The purpose of the field method is to estimate the bonding between polyurethane and the service pipe in a simpler manor. In order to analyse the measurements linear regressions have been carried out, see Figure 12. The axial shear strength is the mean ultimate shear stress over a short piece of pipe.

Regression curves have also been determined for the turning and pulling methods, see Figure 13 and Figure 14. The coefficients are given in Table 3. Confidence intervals containing 95% of all outcomes are given for the coefficient in Figure 15 and Figure 16.

Figure 11: Picture of specimens from turning method.

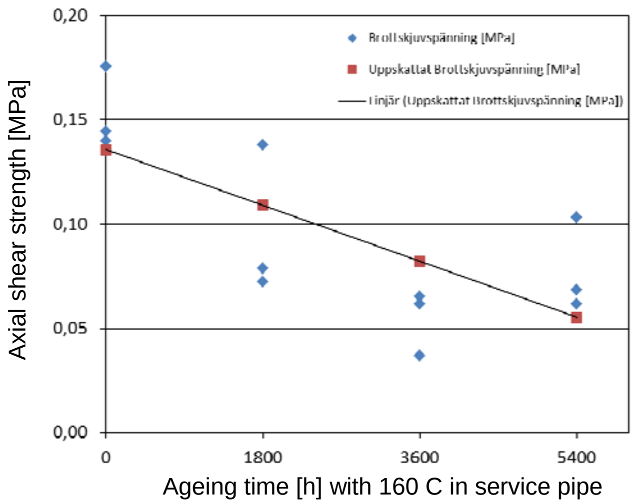

Figure 12: Regression curve for axial shear strength.

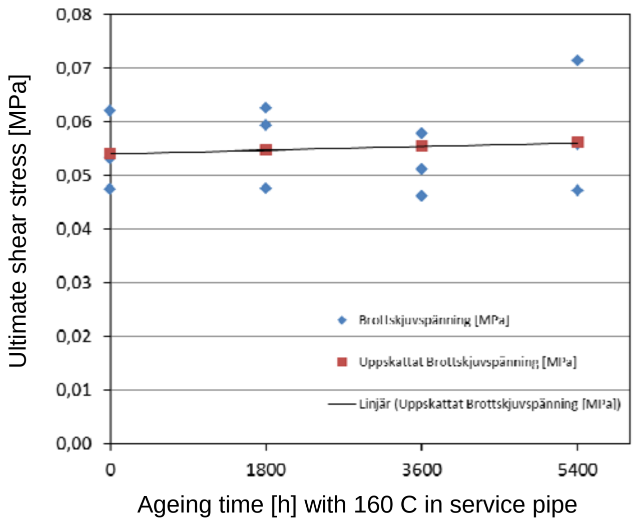

Figure 13: Regression curve for ultimate shear stress obtained from turning method.

The slope of the regression curve for the axial shear strength shows that the strength decreases due to ageing. However the corresponding decrease cannot be found for the turning or pulling method. The decrease of the axial shear strength can be accomplished by a uniform decrease of the bonding around the service pipe, or a non-uniform decrease where the zone without bonding increases. In the latter case the bonding may be more or less unchanged in the areas where it was initially good.

The linear regression of the axial shear stiffness gives a decrease of 14.9 Pa/h=0.13 MPa/year at the temperature 160°C. For the activation energy 150 kJ/mol this means a decrease of 0.0019 MPa/year at the temperature 120°C.

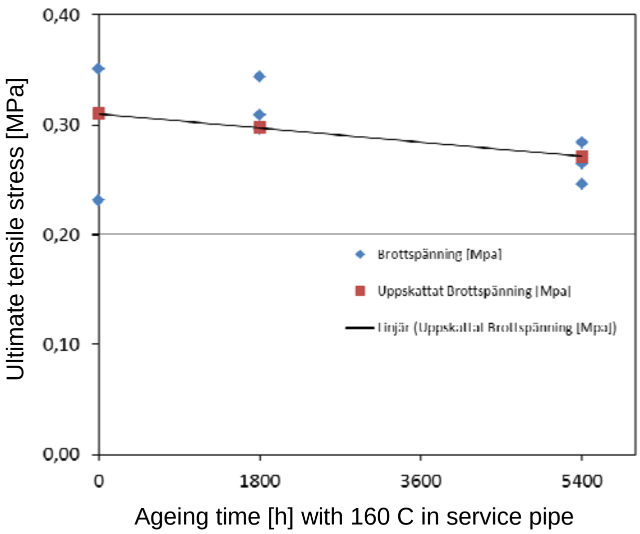

Figure 14: Regression curve for ultimate tensile stress obtained from pulling method.

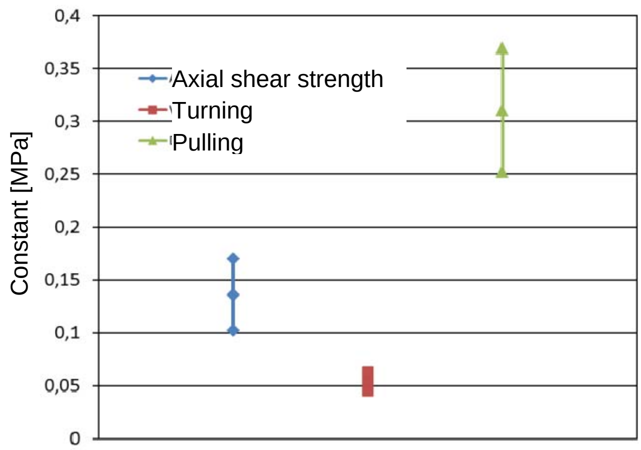

Figure 15: Confidence interval for constant in linear regressions.

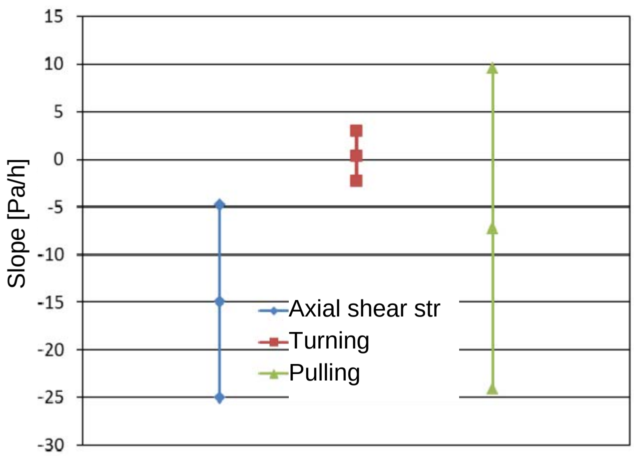

Figure 16: Confidence interval for slope in linear regressions.

Table 3: Coefficients in linear regressions.

Coefficient	Axial shear strength	Turning	Pulling
Constant [MPa]	0.136	0.054	0.310
Slope [Pa/h]	-14.912	0.379	-7.242

Table 4: Partial pressures p(i) and total pressure P_{tot} in cells of foams (density 71-75 kg·m^{-3}) of new pipes. All pressures are given in kPa at room temperature. Ratios of partial pressures of nitrogen and oxygen are also given. District heating pipes were placed at room temperature and hot oil circulated in service pipe during 0-5400h.

Time (h)	0	1800	3600	5400
p(O_2)	2.1	1.0	0.7	0.7
p(N_2)	0.9	3.4	2.0	3.3
p(CO_2)	38	41	41	37
p(CP)	38	35	32	31
P_{tot}	79	81	77	72
p(N_2)/p(O_2)	0.4	3.4	2.7	4.7

RESULTS OF CELL GAS ANALYSES

Table 4 shows the change of the cell gas composition of the foams of district heating pipes where the steel pipes were exposed to circulating hot oil (160°C) during 0-5400h. The isocyanate reaction was not complete at start since p(CO_2) increased until 3600h. Carbon dioxide is formed from the reaction between isocyanate and water. For new pipes, it is often found that p(O_2) is higher than p(N_2). However, oxygen and nitrogen from air will diffuse into the foam and some oxygen will be consumed in oxidation reactions. This is partly seen from the increasing p(N_2)/p(O_2) ratio. The change of the cell gas composition is small and will only give rise to minor changes of the thermal conductivity of the foam.

Table 5: Density, partial pressures p(i), total pressure P_{tot} in cells of old foams studied. All pressures are given in kPa at room temperature. Ratios of partial pressures of nitrogen and oxygen are also given.

Time (h)	GA	GBF	GBR	GCF	GCR	GDR
Density [kg·m^{-3}]	72	70	66	78	81	68
p(O_2)	3.1	1.1	3.4	2.9	12	1.7
p(N_2)	52	14	16	12	58	4.6
p(CO_2)	4.8	25	22	28	25	61
p(CFC11)	58	42	31	33	26	-
p(CP)	-	-	-	-	-	15
P_{tot}	120	83	74	77	122	84
p(N_2)/p(O_2)	17	12	4.8	4.2	4.8	2.7

The cell gas composition of the foam in the old pipes is given in Table 5. The value represents the composition in the middle of the foam. Since the foam of all pipes except GA is thick, samples can be taken at different radial positions of the foam. These samples show that the pressures of oxygen and nitrogen (diffusing into the foam) are higher close to the polyethylene jacket and the pressure of CFC11 (diffusing out of the foam) is higher close to the steel pipe. Carbon dioxide diffuses faster than the other cell gases and exhibits almost the same partial pressure at all radial positions.

All pipes have been in service for over 20 years except pipe GDR, which only has been used for 4 years. The flow pipes GA and GBF have high $p(N_2)/p(O_2)$ ratios indicating oxidation. Pipe GCF has probably only been used at a rather low temperature not giving rise to oxidation.

The thermal conductivity of the cell gas can be calculated from the cell gas composition according to the Wassiljewa equation with the modification of Mason and Saxena. The conductivity of the cell gas in the foam of pipe GBF can be calculated to 0.0122 W/mK at 50°C. If it is assumed that the initial partial pressures of the foam in pipe GBF were 0.5 (O_2), 1 (N_2), 60 (CO_2) and 50 kPa (CFC11), the cell gas conductivity was 0.0121 W/mK at 50°C 25 years ago. Since the contribution from radiation and conduction in the solid polymer is unaffected by the aging, the insulating capacity of pipe GBF is almost unchanged after 25 years!

The diffusion of oxygen and nitrogen into the foam increases the thermal conductivity but the diffusion is slow since the polyethylene jacket is rather thick and some oxygen is consumed in oxidation reactions. Carbon dioxide diffuses faster out of the foam than CFC11. That means that the relative volume of CFC11 (with a very low λ-value) increases and that compensate for the increase of thermal conductivity caused by oxygen and nitrogen.

All pipes except GA are of large dimensions and have thicker polyethylene jackets than according to today's standard, i.e., the jacket of pipe GBF is 9.3-8,8 mm thick but today's standard prescribes only 5.6 mm.

CONCLUDING REMARKS

In the performed tests, the fracture initiation occurs between the service pipe and the polyurethane foam when turning the sample off, while the fracture occurs in the polyurethane foam when pulling the sample off. For the axial shear strength tests the fracture can occur in different ways. Since the temperature in the polyurethane is highest at the service pipe, the degradation is most severe there. This means that the fracture is initiated at the polyurethane at the service pipe, when the technical life due to normal degradation is reached.

The axial shear strength is clearly decreasing during accelerated ageing in the laboratory, but the corresponding reduction has not been found for the pulling or turning method. The advantage with the turning method is that the fracture is initiated at the same position as for the axial shear strength tests. The test methods need to be verified further and adapted for usage in the field.

Requirements on and definitions of technical life have been discussed. It has been concluded that it is not motivated to define the technical life based on the standard requirement in EN 253 on the axial shear strength 0.12 MPa, since the pipe will not be subjected to such a large shear stress between the service pipe and the polyurethane foam. Instead, it is suggested that the definition of life is based on a reduced value. The technical life of a pipe can be estimated based on the measured axial shear strength, an assumed yearly reduction of the axial shear strength at the specific service temperature of the pipe and a life criterion based on the smallest allowable axial shear strength.

The ratio of the partial pressures of nitrogen and oxygen can be calculated from a cell gas analysis. This ratio indicates the extent of oxidation of the foam. In order to be able to make reliable predictions and give target values, further foam samples from other old pipes must be analysed.

The thermal conductivity of a district heating pipe can be calculated from a cell gas analysis. It is also possible to predict the future insulating capacity and heat losses of the district heating system and the indirect environmental impact these losses correspond to. Thus, cell gas analysis is a useful tool for evaluating the status of a district heating system from technical as well as environmental point of view.

Some old pipes studied have a thicker polyethylene jacket than today's standard. The thick jacket, the large dimensions (long diffusion paths) and the slow diffusing insulating gas CFC11 (now forbidden) have contributed to the slow change of the cell gas composition. One pipe had almost the same insulating capacity after 25 years in service.

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