EFFECTS OF MECHANICAL LOADS ON AGEING OF PREFABRICATED DISTRICT HEATING PIPES

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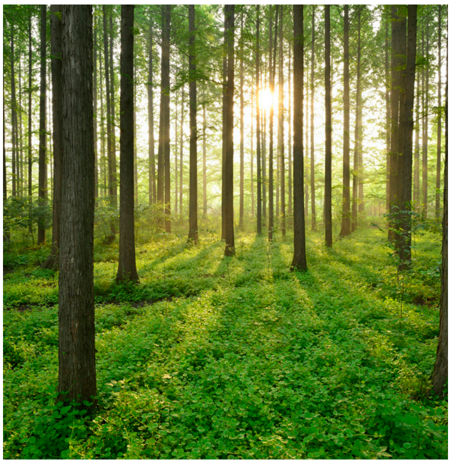

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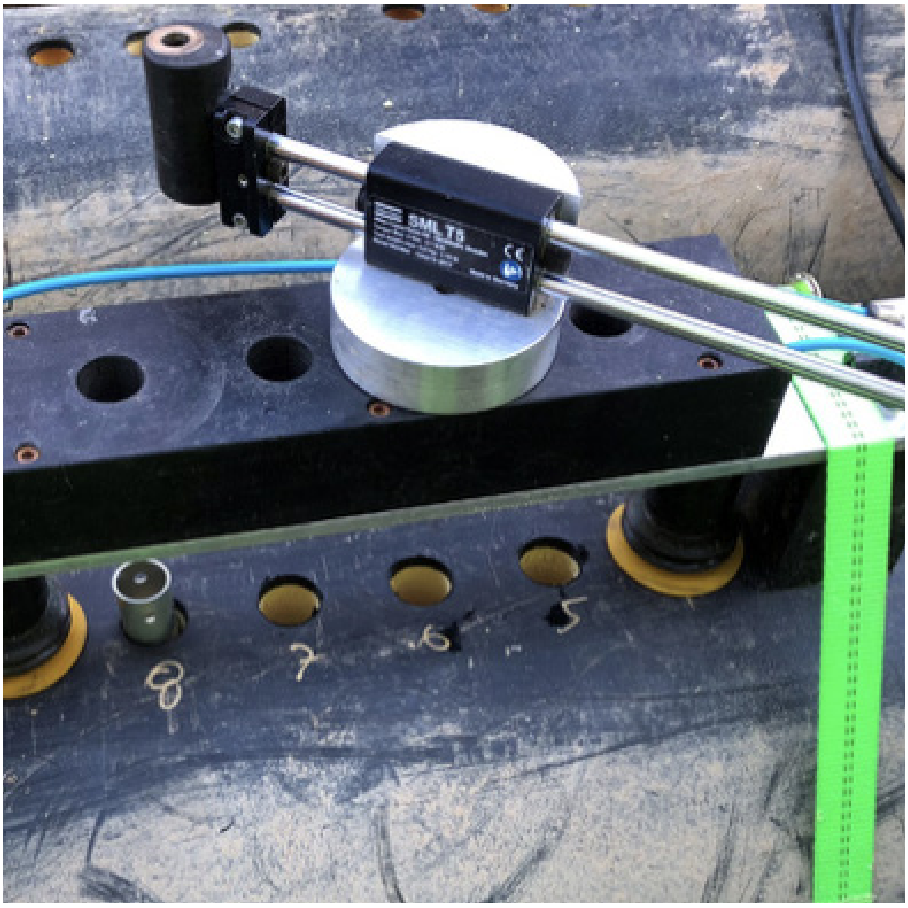

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Effects of mechanical loads on ageing of prefabricated district heating pipes

- manufactured according to EN 253

JAN HENRIK SÄLLSTRÖM
IGNACY JAKUBOWICZ
NAZDANEH YARAHMADI

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Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Foreword

The project has investigated how today's district heating networks can continue to be used over a long period by identifying when and where pipes need to be replaced, in order to avoid unnecessary reinvestments and environmental impact. The focus has been on pre-insulated steel district heating pipes, with particular emphasis on how mechanical loads accelerate degradation. The study analysed deterioration in the field, especially where the insulation separates from the media pipe, which can lead to fatigue and leakage. Experiences from other failure mechanisms have also been compiled. In parallel, new methods have been developed for assessing lifespan and status, through laboratory testing, to enable smart maintenance and selective replacement of worn-out components. The aim was a more reliable calculation model for remaining service life based on actual field conditions.
The project was led by Jan Henrik Sällström, RISE.

The reference group consisted of the following people: Magnus Ohlsson, Öresundskraft – coordinator; Inge Eklund, Mälarenergi; Håkan Bergman, Härnösand Energi och Miljö; Patrick Lauenburg, E.ON Energiinfrastruktur; Sebastian Szajda, Södertörns Fjärrvärme; Johan Renlund, Vattenfall and Mikael Karlsson, Energiforsk.

The project is part of the FutureHeat programme, whose long-term goal is to contribute to the vision of a sustainable heating system with successful companies that harness new technological opportunities, and where societal investments in district heating and cooling are utilised in the best possible way. This project is included in the programme's third stage.

The programme is led by a steering group consisting of Cecilia Bergquist (chair), Halmstad Energi och Miljö; Stefan Hjärtstam, Borås Energi och Miljö; Peter Mattsson, Södertörns Fjärrvärme; Svante Carlsson, Skellefteå Kraft; Stina Berg, Tekniska Verken i Linköping; Dado Hadziomerovic, Vattenfall; Fabian Levihn, Stockholm Exergi; Lisa Granström, Mälarenergi; Magnus Ohlsson, Öresundskraft; Magnus Revland, Finspångs Tekniska Verk; Harald Andersson, E.ON Energiinfrastruktur; Linda Östberg, Karlstads Energi; Ulf Lindqvist, Jämtkraft; Patrik Grönbeck, Norrenergi; Erik Axelsson, Göteborg Energi.

Mikael Karlsson, Energiforsk

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

The project investigated whether prefabricated district heating pipes manufactured according to EN 253, in the sliding zones, where they are exposed to mechanical stress, degrade faster than at other positions. The indications were deterioration of adhesion between the service pipe and the insulation, and changes in the chemical structure of the insulation. Other failure mechanisms besides loss of adhesion were compiled.

Status assessments of supply pipes in the field, in and outside the pipes' sliding zones, were made with RISE PipeOpsy™. The most important parts are the RISE Plug method in the field, chemical analysis of the polyurethane insulation in the laboratory and a conversion of the service time to an equivalent one at the reference temperature. Furthermore, other failure mechanisms were compiled via an international workshop and failure statistics.

In the cases investigated, the equivalent service time at a constant reference temperature of 95 °C is around 20 years. Considering that the current requirement is a service life of 30 years at a continuous operating temperature of 120 °C, the tested pipes have been in operation for a relatively short time.

Degradation of polyurethane and deterioration of adhesion in prefabricated district heating pipes was assessed to be greater in the sliding zone than in the fixed zone, which confirms the theory on which this study is based. It is precisely in the sliding zone that adhesion needs to be good. In the cases investigated, no extensive degradation of the district heating pipes had yet occurred.

Other types of failures than loss of adhesion are often related to joints in the casing or service pipes. For joints, some failures are assessed to be age-related and others not. Non-age-related failures are due to errors that occur due to mistakes during installation, design or manufacturing of components.

Failures of joints due to age can be shrink-type casing joints that begin to leak over time, when the mastic dries and seals less well or when the joints are damaged by many movements in the ground. Furthermore, small pores in welded joints in service pipes from manufacturing and installation, which are exposed to both fatigue and corrosion, can lead to leakage over time.

Keywords

Prefabricated district heating pipes, field measurements, PipeOpsy, degradation, status assessments, adhesion, fixed zone, sliding zone

Sammanfattning: Effekt av mekanisk last på åldring av prefabricerade fjärrvärmeledningar

I projektet undersöktes om prefabricerade fjärrvärmeledningar tillverkade enligt EN 253, i glidzonerna, där de utsätts för mekanisk belastning, bryts ner fortare än på andra ställen. Indikationerna var försämrad vidhäftning mellan medierör och isolering och förändringar i den kemiska strukturen hos isoleringen. Andra haverimekanismer vid sidan av förlorad vidhäftning sammanställdes.

Statusbedömningar av framledningar i fält i och utanför ledningarnas glidzoner gjordes med RISE PipeOpsy™. De väsentligaste delarna är RISE Pluggmetod i fält, kemisk analys av polyuretanisoleringen i laboratoriet och en omräkning av driftstiden till en ekvivalent sådan vid en referenstemperatur. Vidare sammanställdes andra haverimekanismer via en internationell workshop och skadestatistik.

I de undersökta fallen är den ekvivalenta driftstiden vid en konstant referenstemperatur 95 °C omkring 20 år. Med tanke på att det gällande kravet är en livslängd på 30 år vid kontinuerlig driftstemperatur på 120 °C, så har de provade ledningarna varit i drift en relativt kort tid.

Nedbrytning av polyuretan och försämring av vidhäftning hos prefabricerade fjärrvärmeledningar bedömdes vara större i glid- än i fixzon, vilket bekräftar teorin som denna undersökning har utgått ifrån. Det är just i glidzonen som vidhäftningen behöver vara god. I de undersökta fallen hade ingen omfattande nedbrytning av fjärrvärmeledningarna skett än.

Andra typer av haverier än förlorad vidhäftning är ofta relaterade till skarvar hos mantel eller medierör. För skarvar bedöms vissa haverier vara åldersrelaterade och andra inte. Icke-åldersrelaterade beror på fel som uppstår på grund av misstag vid installation, konstruktion eller tillverkning av komponenter.

Haverier av skarvar som beror på ålder kan vara mantelskarvar av krymptyp som med tiden börjar läcka då mastic torkar och tätar sämre eller då skarvarna skadas av många rörelser i mark. Vidare kan små porer i svetsfogar i medierör från tillverkning och installation, som utsätts för både utmattning och korrosion, med tiden leda till läckage.

Nyckelord

Prefabricerade fjärrvärmeledningar, fältprovningar, PipeOpsy, nedbrytning, statusbedömningar, vidhäftning, fixzon, glidzon

Extended Summary: Effects of mechanical loads on ageing of prefabricated district heating pipes

The project investigated whether prefabricated district heating pipes manufactured according to EN 253, in the sliding zones, where they are exposed to mechanical stress, degrade faster than at other positions. The indications were deterioration of adhesion between the service pipe and the insulation, and changes in the chemical structure of the insulation. Other failure mechanisms besides loss of adhesion were compiled.

Status assessments of supply pipes in the field, in and outside the pipes' sliding zones, were made with RISE PipeOpsy™. The most important parts are the RISE Plug method in the field, chemical analysis of the polyurethane insulation in the laboratory and a conversion of the service time to an equivalent one at the reference temperature. Furthermore, other failure mechanisms were compiled via an international workshop and failure statistics.

RISE Plug method is based on that uncovered plugs (drill cores) of insulation are twisted loose from the service pipe, see Figure 1. During the test, the operation of the pipeline can continue. The rig allows for support and steering during both sample preparation and measurement of the torque. Aluminium sleeves are glued to the plugs to be able to apply the torque to each plug.

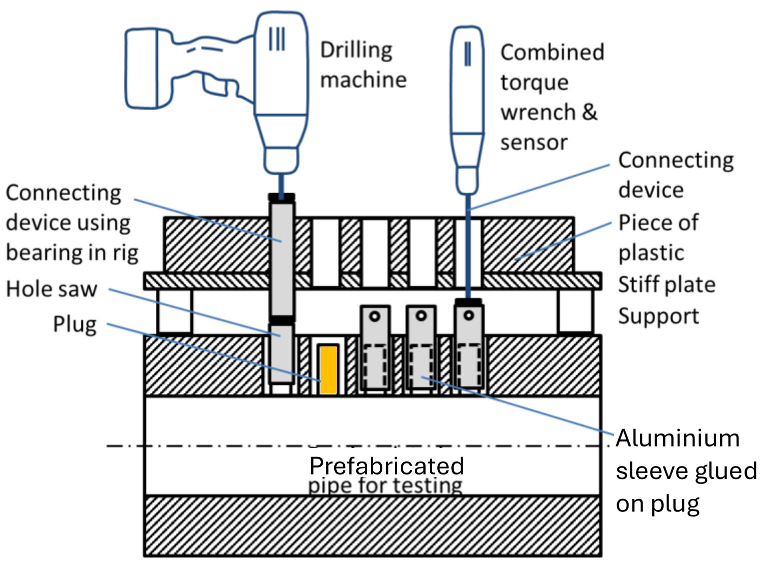

Figure 1: Sketch of RISE plug method

In RISE PipeOpsy™, chemical changes in the molecular structure of polyurethane are studied using FTIR spectroscopy (Fourier Transform Infra-Red) with ATR (Attenuated Total Reflectance). Degradation of polyurethane usually begins with the dissociation of the urethane bonds C=O and N-H, see Figure 2. Absorption indices are determined for these bonds corresponding to the wavenumbers 1712 cm^{-1} and 1512 cm^{-1}, respectively. Each absorption spectrum is normalized with the absorption peak at 1595 cm^{-1}, which represents the thermally stable double bonds between carbon atoms in the aromatic rings.

Thin slices 1-2 mm thick of the plugs from field measurements, which have been in contact with the service pipe and those that have been located far (about 20 mm) from the service pipe are studied. The purpose is to analyse the degradation of the polyurethane at the service pipe. The ratio of absorption indices of polyurethane in contact with and far from the service pipe is a measure of the degradation of the polyurethane at the service pipe.

For the conversion of the service time, an acceleration factor *Af* equal to 2.5 is used. This value has shown good agreement between status and service time for different operating temperatures. When the operating temperature is increased by 10 °C, the chemical reactions are assumed to proceed *Af* times faster. The actual service time and the operation temperatures are converted to an equivalent operation time at the reference temperature 95 °C. The same damage or degradation is assumed to occur in both cases, but the impact is easier to quantify in the latter case. Furthermore, this makes it easier to compare what different pipelines have been exposed to.

In the cases investigated, the equivalent service time at a constant reference temperature of 95 °C is around 20 years. Considering that the current requirement is a service life of 30 years at a continuous operating temperature of 120 °C, the tested pipes have been in operation for a relatively short time.

Degradation of polyurethane and deterioration of adhesion in prefabricated district heating pipes was assessed to be greater in the sliding zone than in the fixed zone, which confirms the theory on which this study is based. It is precisely in the sliding zone that adhesion needs to be good. In the cases investigated, no extensive degradation of the district heating pipes had yet occurred.

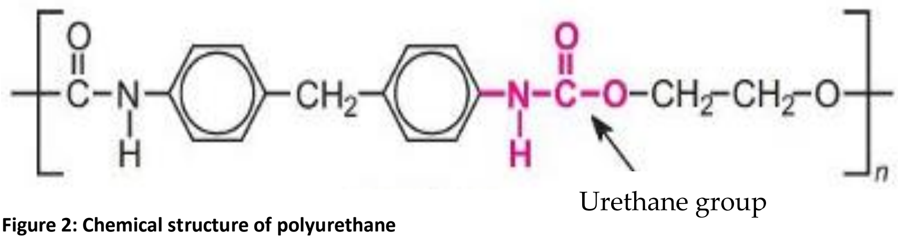

Figure 2: Chemical structure of polyurethane

For the chemical analysis (FTIR), the deterioration is greater in the sliding zone than in the fixed zone with a probability of 97.5 %. In some individual cases of the positions examined, there is a clear difference between the sliding and fixed zones. For the adhesion, the deterioration of this is greater in the sliding zone than in the fixed zone with a probability of 93 %.

Other types of failures, than loss of adhesion, are often related to joints in the casing or service pipes. For joints, some failures are assessed to be age-related and others not. Non-age-related failures are due to errors that occur due to mistakes during installation, design or manufacturing of components.

Failures of joints due to age can be shrink-type casing joints that begin to leak over time, when the mastic dries and seals less well or when the joints are damaged by many movements in the ground. Furthermore, small pores in welded joints in service pipes from manufacturing and installation, which are exposed to both fatigue and corrosion, can lead to leakage over time.

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1 Introduction

Large sums have been invested in district heating networks over the years, and replacing the district heating pipes would lead to huge reinvestments. Therefore, there are strong reasons to use the networks for as long as technically possible.

Cost-effective and environmentally friendly maintenance, based on selective replacement of worn-out parts, can significantly extend the service life. Furthermore, the operation of the networks should be optimized so that factors affecting the service life of the pipes are also considered. The project focused on prefabricated district heating pipes manufactured according to EN 253 with steel service pipes, polyurethane insulation and polyethylene casing. A key failure mechanism in these pipes is the loss of adhesion between the insulation and the service pipes, which leads to the service pipes being able to move freely. Then the steel near bends can be subjected to fatigue and the insulation in bends can be compressed and destroyed.

Under normal operating conditions, district heating pipes are exposed to significant temperature variations due to variations in customers' demands and the optimization of the heat production. When the pipes interact with the ground, this leads to varying mechanical loads on the pipes. Previous experiments have shown that the insulation in mechanically loaded district heating pipes under high ageing temperatures degrade faster than in unloaded pipes, which age at the same temperature [1]. This results in, the adhesion between the insulation and the service pipe decreases faster under varying loads.

1.1 AIM AND PURPOSE

An important aim of the project was to confirm that the insulation in mechanically loaded pipes age faster than in pipes without mechanical loads. To find out this, the status of older district heating pipes in operation in the sliding zones, where mechanical load on the insulation is assumed to be the greatest, and the same pipes in the fixed zones, where mechanical load is assumed to be small/negligible, were investigated.

The result is useful for determining where status assessments should be made, and generally which parts of the district heating networks degrade the fastest. Figure 1.1 shows a sketch of a district heating pipeline. The axial force is built up in the sliding zone by the friction between the casing and the soil, which causes shear stresses in the insulation. The pipeline is fixed far from bends and at symmetry points in the network. A second goal was to compile other types of failures in the district heating networks.

The purpose of the project is to develop relevant knowledge as a basis for improved maintenance of district heating networks, which supports the selective replacement of parts. Status assessments in the networks and better lifetime estimates are necessary tools for optimal maintenance of the networks.

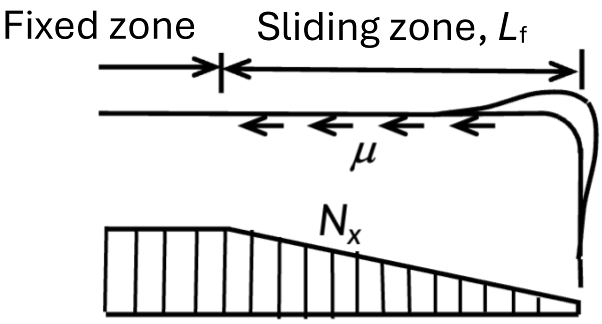

Figure 1.1: Sketch of district heating pipeline consisting of straight pipes that meet at bend. Axial force increases in the sliding zone with length L_f when pipe becomes longer with increasing temperature and slides in soil. Friction between casing and soil leads to increasing axial force and shear stresses in insulation. If friction is constant in sliding zone, axial force increases linearly

In the project, status assessments have been made in the field in and outside the sliding zones of the pipelines with RISE PipeOpsy™. Furthermore, other failure mechanisms have been compiled via an international workshop and failure statistics.

1.2 PREVIOUS STUDIES

This project is based on previous studies conducted at RISE. In a previous project within FutureHeat [2], a literature review on degradation mechanisms, which are significant for prefabricated district heating pipes, is given. Development of simpler methods for status assessment was presented in 2012 [3], as a result a national project and was later applied in an international project [4]. Degradation of polyurethane, accelerated ageing and natural ageing have been studied in several published studies [5], [6]and [7]

2 PipeOpsy

RISE PipeOpsy™ [8], which is the registered RISE method 5790, consists of the RISE Plug Method, chemical analysis of the polyurethane insulation, a conversion of the service time, measurement of the thermal conductivity of the insulation and restoration of examined district heating pipes.

2.1 FIELD MEASUREMENTS – RISE PLUG METHOD

In the previous project [2] within FutureHeat, a method was developed for field measurements of the adhesion strength between insulation and service pipe. The method is based on that uncovered plugs (drill cores) of insulation are twisted loose from the service pipe and the applied torques are measured. During the test, the operation of the pipeline can continue. A specially developed rig is used, which allows for support and steering during both sample preparation and torque measurements, see Figure 2.1. Aluminium sleeves are glued to the plugs to be able to apply the torque to each plug.

A combined torque wrench and sensor have been used in the measurements, but also a simpler torque wrench has been used. During the field measurements, the temperature of the service pipe has been measured to be able to assess its influence on the measurement result.

To obtain a good statistical basis and a low measurement uncertainty with respect to the average value, testing with approximately seven plugs is required. The shear strength τ_u [Pa] is calculated from the measured torque M [Nm] and the plug diameter d = 0.027 m according to

$$\tau_u = \frac{16\,M}{\pi d^3} \qquad (1)$$

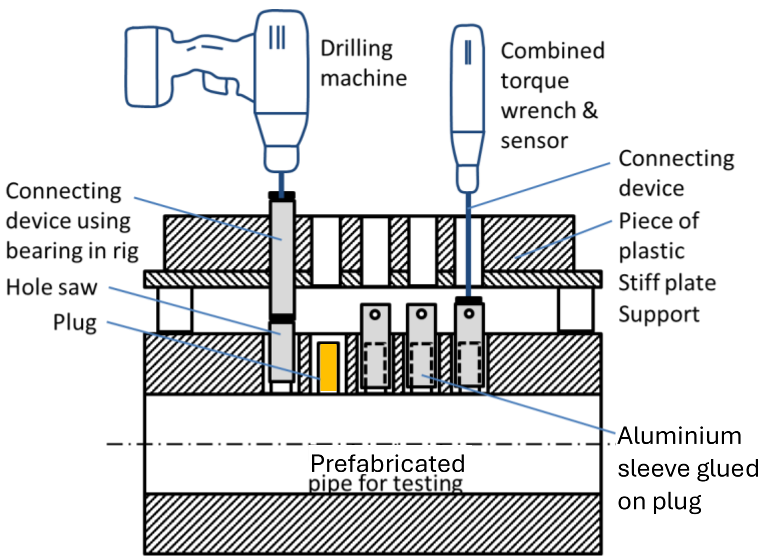

Figure 2.1: Sketch of RISE plug method

2.2 CHEMICAL ANALYSIS

Chemical changes in the molecular structure of polyurethane can be studied using a spectroscopy method. In this case, FTIR (Fourier Transform Infra-Red) spectroscopy with ATR (Attenuated Total Reflectance) attachment is used. A device irradiates the material sample with infrared (IR) light and a spectrum is obtained from the wavenumbers that are absorbed. The method can be used to identify organic and inorganic materials. It can also be used to study changes in molecular structure, *e.g.*, as a result of oxidation.

Degradation of polyurethane usually begins with the dissociation (chemical degradation) of the urethane group and can be studied using FTIR by measuring changes in the intensity of two characteristic peaks corresponding to the chemical bonds C=O and N-H, see Figure 2.2. The absorption indices for the bonds C=O and N-H at wavenumbers 1712 cm^{-1} and 1512 cm^{-1}, respectively, are calculated. Each spectrum is normalized with the absorption peak at 1595 cm^{-1}, which represents the thermally stable double bonds between carbon atoms in the aromatic rings.

Thin slices 1-2 mm thick of the plugs from field measurements, which have been in contact with the service pipe and those that have been located far (about 20 mm) from the service pipe are studied. The purpose is to analyse the degradation of the polyurethane which has been in contact with the service pipe. The polyurethane that has been located far from the service pipe is used as a reference, and here it is expected that no degradation has occurred. The samples are placed on the ATR crystal and then pressed against the surface to obtain optimal contact. At least three samples from each position are analysed with FTIR.

When IR radiation penetrates a sample, some of the radiation is absorbed by the sample (absorbance). The resulting signal at the detector gives an absorption spectrum, which is unique to the polyurethane and constitutes a molecular "fingerprint" of the material. Figure 2.3 shows FTIR spectra of samples taken in contact with and 20 mm from the service pipe of a pipeline subjected to accelerated ageing at 140 °C. Differences in absorbance levels indicate differences in degradation.

The peaks in the spectra for the wavenumbers 1712 cm^{-1} and 1512 cm^{-1} give, by averaging of at least three samples, the absorption indices belonging to the C=O and N-H bonds, respectively. For each peak, the ratio of indices determined from the polyurethane in contact with the service pipe and far away is formed, which provides a measure of the degradation.

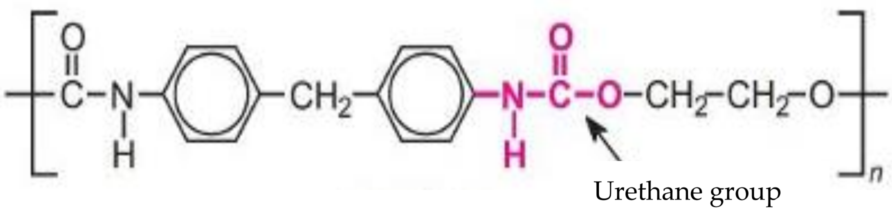

Figure 2.2: Chemical structure of polyurethane

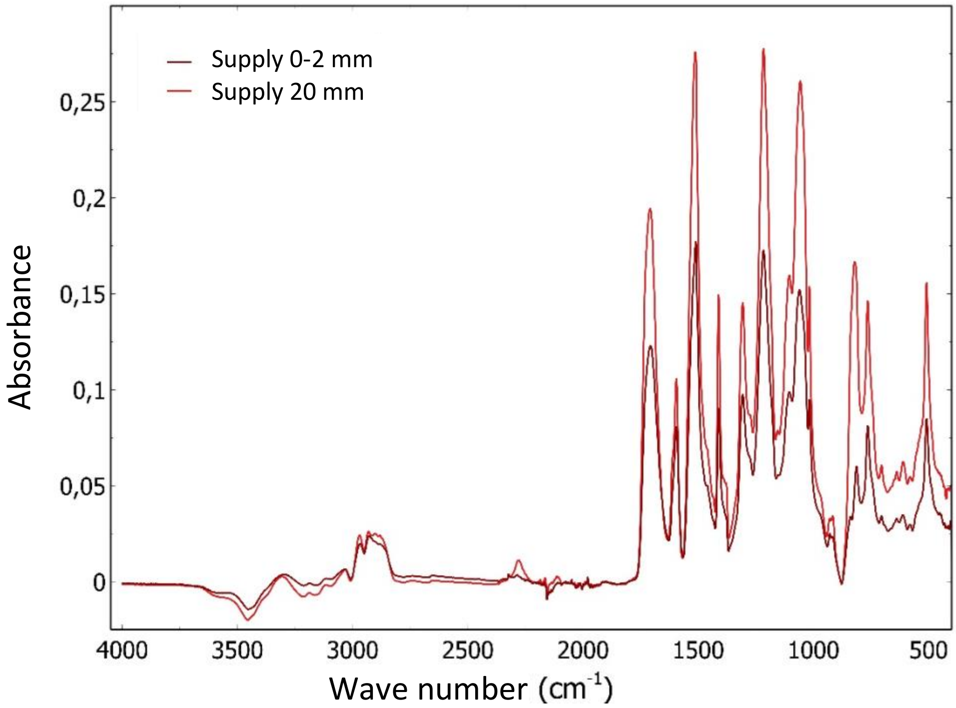

Figure 2.3: FTIR spectra of samples taken 0-2 and 20 mm from service pipe of accelerated aged pipe at 140 °C

2.3 CONVERSION OF SERVICE TIME

The operating temperature in district heating networks varies over time depending on the season and other operating conditions. The latter can vary between different district heating networks. To estimate of the thermal stress a particular pipeline has been exposed to, the pipeline's service time is converted to an equivalent service time (age) at the reference temperature of 95 °C. The conversion makes it possible to compare the age of different pipelines with different service times and operating temperatures from different networks.

The conversion uses an acceleration factor *Af* chosen to be 2.5, which is consistent with values reported in the scientific literature and has shown good agreement between status and service time for different operating temperatures. When the operating temperature is increased by 10 °C, the chemical reactions are assumed to proceed *Af* times faster. Figure 2.4 illustrates the method for *Af* = 2.

The method is based on a rule of thumb, which means that a reaction doubles in rate for every 10 °C increase in temperature (*Af* = 2) and is usually called the Q10 rule. Let us assume that a chemical reaction follows the Arrhenius equation. Then the temperature dependence of the reaction rate is given by

$$k_i = Ae^{-E_a/RT_i} \quad (2)$$

Here, the rate constant k_i is at the absolute temperature level T_i. Equation (2) includes the reaction's activation energy E_a, a pre-exponential factor A and the ideal gas constant R = 8.314 J/(K mol). If you know the value of the activation energy, you can use the Arrhenius equation (2) to calculate the acceleration factor. Suppose that

$$T_1 = T_2 + 10 \text{ K} \quad (3)$$

Table 2.1: Relationship between acceleration factor at 95 ° and activation energy

Parameter	Notation	Case I		Case II	
	Af	2		2,5	
Reference temperature	T_0	95	°C	95	°C
Temperature increase	ΔT	10	°C	10	°C
Activation energy	E_a	80	kJ/mol	106	kJ/mol

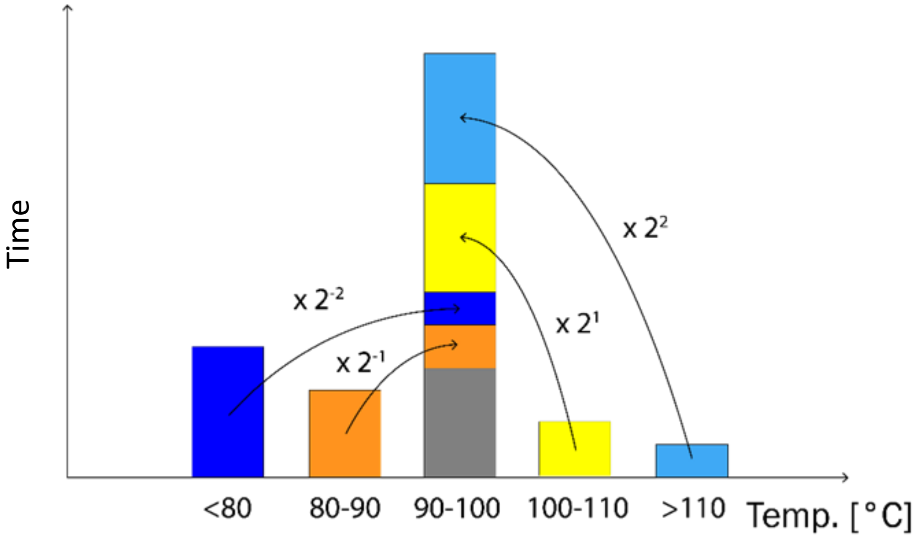

Figure 2.4: Schematic example for a simple conversion of service time at different temperatures, to time at reference temperature if Af is 2

Then the acceleration factor becomes

$$Af = \frac{k_1}{k_2} = \exp\left[-\frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \quad (4)$$

Table 2.1 gives the relationship between the acceleration factor and the activation energy when the temperature is raised from 95 to 105 °C.

2.4 THERMAL CONDUCTIVITY

Thermal conductivity of polyurethane insulation can also be measured in the field with the Thermtest TLS-100 according to the ASTM D5334 standard [9]. This is a hand-held device with a needle-shaped sensor, which is 100 mm long and 2 mm in diameter. The sensor is pressed into the insulation via a plug hole. Before measuring the conductivity, one should wait about 10 minutes so that the frictional heat generated during the pressing has dissipated. No measurements of thermal conductivity were made in the present project.

2.5 RESTORATION

After the field test, the pipeline is restored by pressing prepared cylinders of polyurethane insulation into the holes. The casing is restored with welding plugs, which are heated in a special tool.

3 Analysis of results of measurements

In total, 11 paired field measurements were carried out on pipes in trenches or cut out pieces. The measurements were carried out on the supply line in two positions where the pipes slide relative to the soil in one position and are fixed in the other.

At these positions, the pipeline should otherwise be completely identical, *i.e.*, the same dimension, the same make, installed at the same time and exposed to the same temperature history. During the measurements, samples were also taken from the return pipeline in case it would be good to have a reference for the later analysis. The measurements were carried out according to PipeOpsy™, see Chapter 2.

Table 3.1 lists the locations where pipelines have been tested either in situ or after excavation. The list indicates the pipeline's service time and an equivalent service time at the reference temperature of 95 °C. The tests at Jordbro heating plant and Södra Jordbro concern a pipeline that supplies water with a constant operating temperature of 120 °C to an industry. The pipelines at these positions were not of the same age and could therefore not be treated as a pair from the sliding and fixed zones, respectively.

Table 3.1 also indicates the year of installation and the probable propellant. The propellant CFC11 was banned in Sweden on 1 July 1991 and cyclopentane became available in the mid-1990s. In the transition between these propellants, carbon dioxide, soft freons (HCFC) and 1.1.1. trichloroethane were used [10].

Table 3.1: Field measurement locations, installation year, probable propellant and service times [yrs]

Location	Installa-tion year	Probable propellant	Service time [yrs]	Equivalent service time at 95 °C [yrs]
Kabelgatan, Gbg	1976	CFC11	47	19
Errarpsvägen, Ägh	1997	C-pentane	26	23
Huskvarnavägen, Jkg	1995	CO_2	28	21
Bergavägen, Åkersberga	1981	CFC11	42	13
Kanalgatan, Eslöv	1985	CFC11	39	12
Ekhagsringen, Jkg	2000	C-pentane	24	18
Hermansvägen, Jkg	1992	CO_2	32	24
Södra Jordbro	1997	C-pentane	27	232
Jordbro v.v.	2015	C-pentane	9	77
Ölandsgatan, Ägh	1995	CO_2	29	26
Ristippen, Lund	1970	CFC11	54	25
Lantmätarvägen, Bro	1980	CFC11	44	36

3.1 FIELD MESUREMENTS

In the field test, the torque required to twist loose the plug is measured. In the previous project [2], a sufficient axial shear strength was estimated to be 0.04 MPa. Through correlation studies, it has been concluded that the ultimate shear stress at the periphery of the plug (shear strength measured with the plug method) is three times higher for adhesion failure, i.e. 0.12 MPa [2].

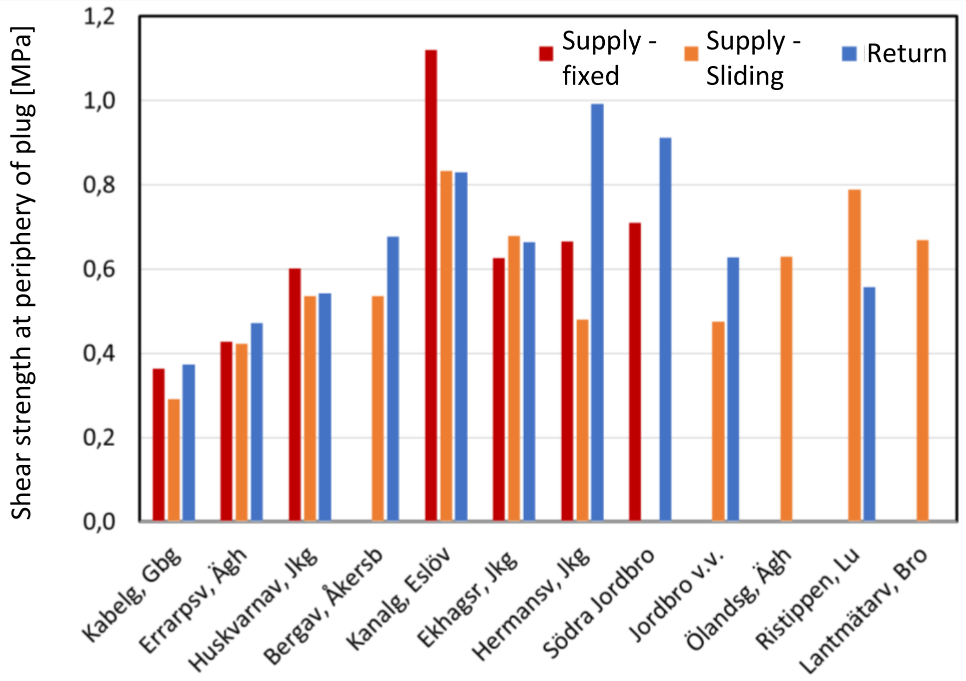

Figure 3.1: Shear strength at periphery of plug for different locations

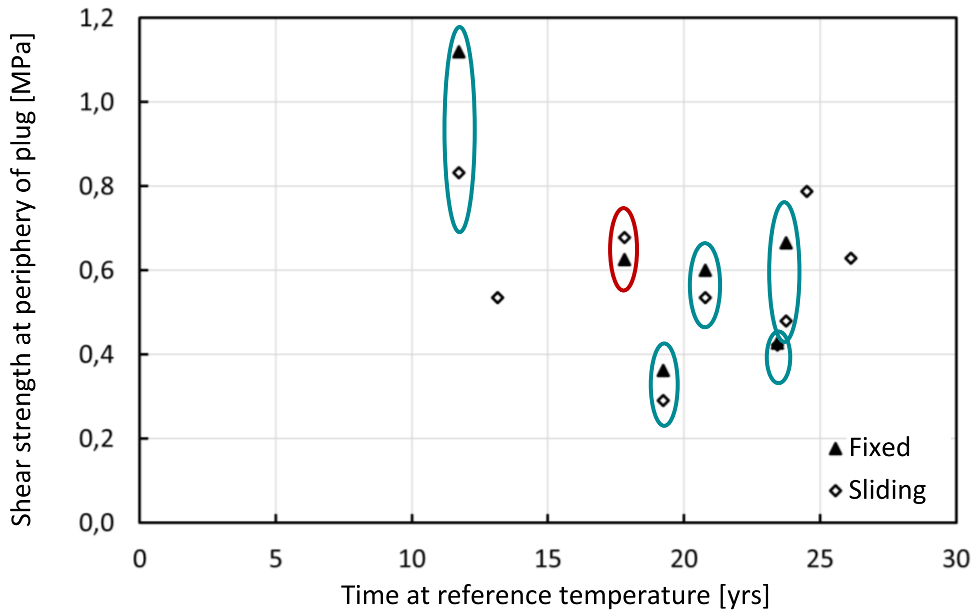

Figure 3.2: Shear strength at the periphery of plug as function of equivalent service time at 95 °C. Results from South Jordbro and Jordbro heating plants are not reported here. Neither are results from Bro, as information about pipelines was uncertain

For different measurement locations, the results of the shear strength are shown in Figure 3.1 For Bergavägen in Åkersberga, Ölandsgatan in Ängelholm, Ristippen in Lund and Lantmätarvägen in Bro, the adhesion of the supply line in the fixed zone was so low that the plug came loose during the preparation of the plug.

Figure 3.2 shows the shear strength as a function of equivalent service time at 95 °C. Only six paired measurements of the shear strength have been carried out with clear information. In all but one case, these measurement results are as expected. The expect result is greater shear strength in the fixed zone than in the sliding zone, as the degradation is assumed to have progressed further in the sliding zone because of the mechanical loading. Deviations from this may be due to various circumstances, but after manufacturing, there may be variations in the density and the shear strength along the pipes. This is especially true for single piece manufacturing.

3.2 CHEMICAL ANALYSES

The plugs taken from the field have been analysed in the laboratory with FTIR. Indexes are calculated for the IR peaks corresponding to C=O and N-H bonds in polyurethane insulation in contact with and far from the service pipe. The insulation far from the service pipe is used as a reference. The ratio between the indices is a measure of the degradation of the polyurethane at the service pipe. The results are shown for each location in Figure 3.3 and Figure 3.4. The C=O bond is the one that is usually breaks earlier during thermo-oxidative degradation. The corresponding index ratios are below 0.8 for some locations, which indicates that some degradation has occurred. The index ratio for N-H is usually higher and shows degradation only for a few locations.

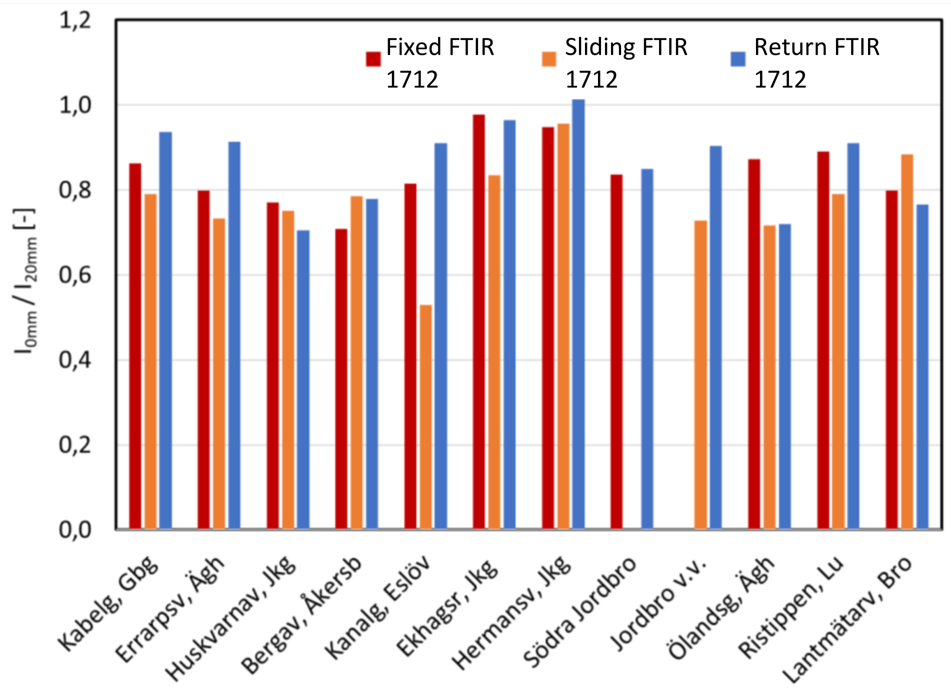

Figure 3.3: Index for 1712 cm^{-1} (Bond C=O in Urethane group) at different locations

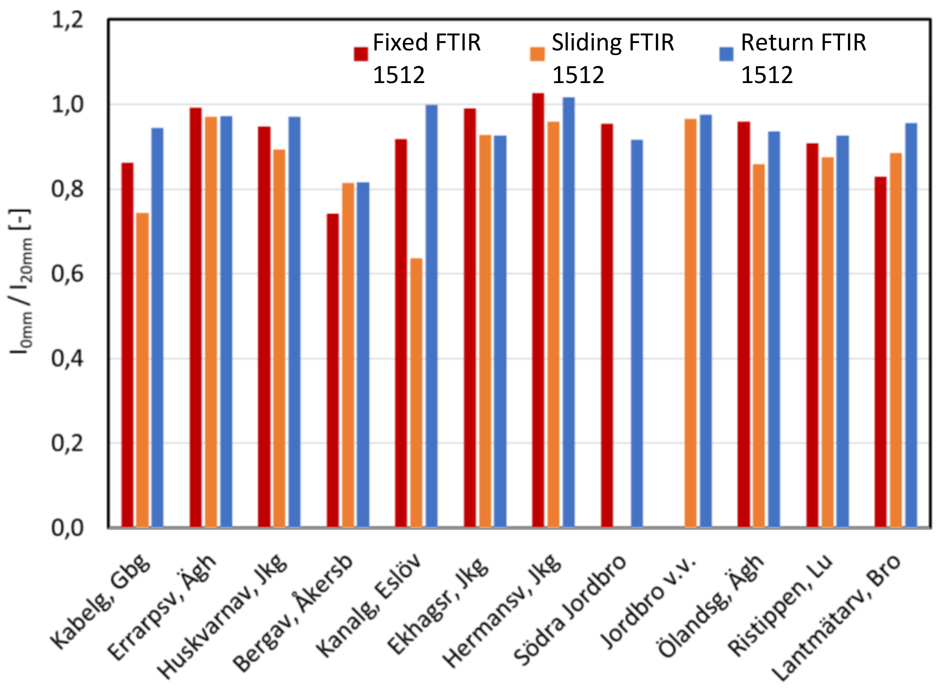

Figure 3.4: Index for 1512 cm-1 (Bond N-H in Urethane group) at different locations

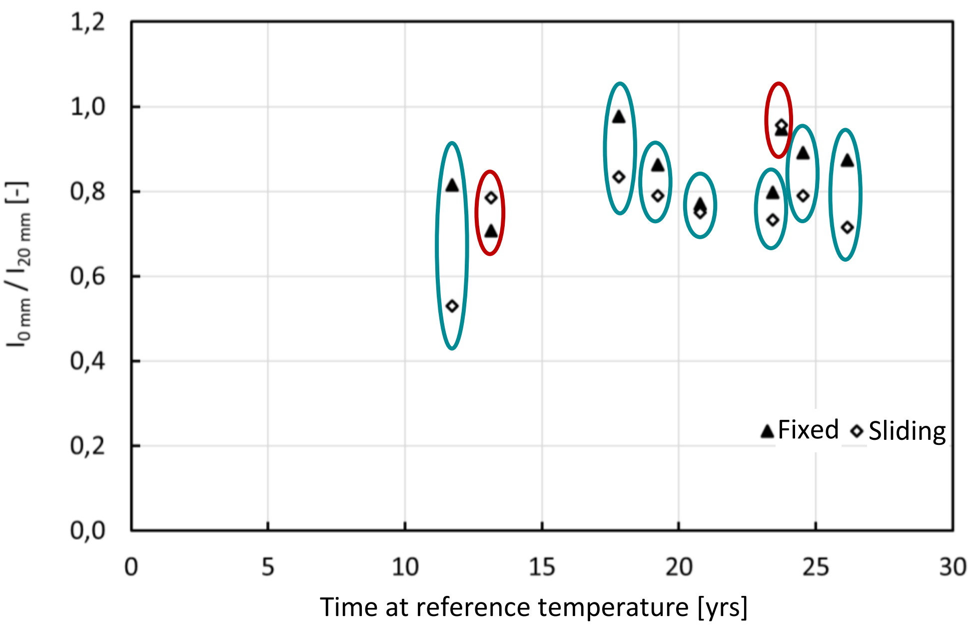

Figure 3.5: Index for 1712 cm-1 (Bond C=O in Urethane group) as function of equivalent service time at 95 °C

Table 3.2: Difference between values belonging to fixed and sliding zones. For each pair, difference is formed, after which average, standard deviation, t-distribution and upper and lower limits are determined. With probability of 95 %, difference lies between specified limits

	Average	St dev	Number of pairs n	$t_{97,5\,\%,\,n-1}$	Upper limit	Lower limit
Adhesion [MPa]	0,094	0,124	6	2,571	0,223	-0,036
Index ratio for C=O [-]	0,084	0,106	9	2,306	0,165	0,003
Index ratio for N-H [-]	0,074	0,095	9	2,306	0,147	0,001

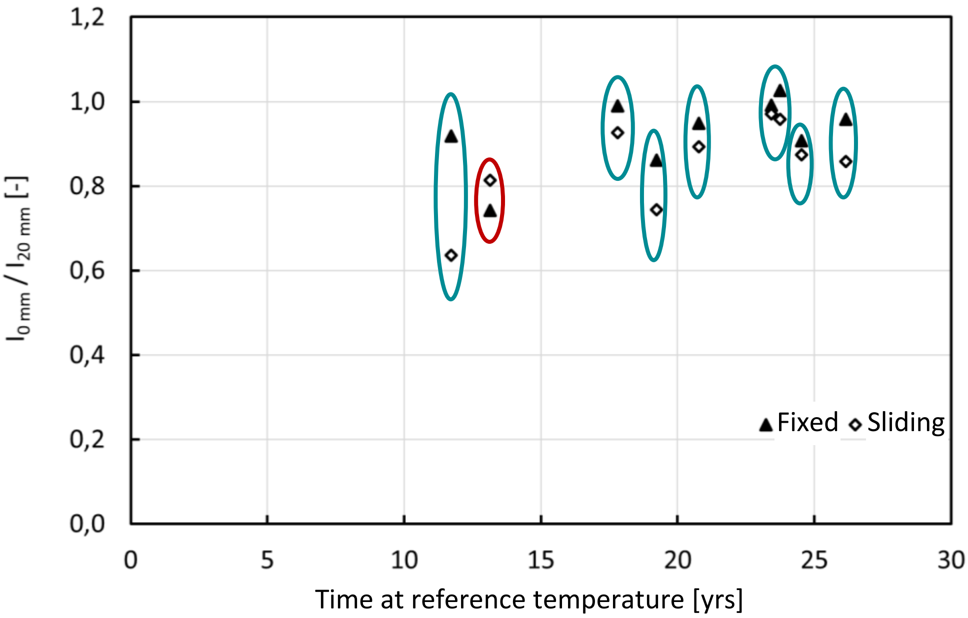

Figure 3.6: Index for 1512 cm^{-1} (Bond N-H in Urethane group) as function of equivalent service time at 95 °C.

In Figure 3.5 and Figure 3.6, ratios of indices are shown as a function of the equivalent service time at 95 °C. In these cases, there are nine paired measurements of indices for measurement locations with clear information. For the C=O bond at wavenumber 1712 cm^{-1}, all ratios of indices are as expected except for two, see Figure 3.5 again. In the fixed zone, it is expected less degradation and a higher value of the index ratio. For the N-H bond at wavenumber 1512 cm^{-1}, all indices are as expected except for one, see Figure 3.6 again.

Pictures of plugs from the field tests are presented in Appendix A. During thermo-oxidative degradation of polyurethane, it darkens, meaning that the intensity of the brown colour is a measure of degradation.

3.3 CONVERSION OF SERVICE TIME

Table 3.1 shows the equivalent operating time at 95 °C. Most pipes have not been in use at a high operating temperature for more than about 20 years. Considering that the requirement in the standard EN 253 [11] on a service life of 30 years at a continuous operating temperature of 120 °C, the tested pipes have been in service for a relatively short time.

3.4 DISCUSSION

To determine whether the hypothesis that the degradation is greater in the sliding zone than in the fixed zone is true, the difference between the results belonging to the fixed and sliding zones is formed for each pair of tests. If the hypothesis is true, the difference should be positive.

Table 3.2 shows the pairwise differences for adhesion and index ratios. The average value $\overline{x}$ and the standard deviation s of the differences are calculated for each type of result. With the probability (confidence) 95 %, the true values of the differences lie within the interval

$$\hat{x} = \overline{x} \pm t_{97,5\%,N-1} \times \frac{s}{\sqrt{N}} \tag{5}$$

The number of pairs is N and the 97.5% quantile of the t-distribution with (N-1) degrees of freedom is denoted $t_{97,5\%,N-1}$.

For the ratios of the indices, the difference is above zero, so it shows that the degradation is greater in the sliding zones, see Table 3.2. With a probability of 97.5%, the difference in the ratios of the indices is greater than zero and with the same probability, the indices in the fixed zone are greater than those in the sliding zone.

The probability that the difference in adhesion is greater than zero is lower than 97.5 %. If the probability is lowered in Equation (5), the lower bound of the difference of the adhesion can exceed zero. If the limits are determined for probability 86%, then the lower bound will exceed zero. With only 93 % confidence, it can be stated that the adhesion in the fixed zone is greater than in the sliding zone.

The ratios of the indices belonging to C=O indicate that no extensive degradation has occurred for the supply line at Bergavägen in Åkersberga, Ölandsgatan in Ängelholm, Ristippen in Lund and Lantmätarvägen in Bro. The lack of adhesion in these positions is therefore assumed to be due to circumstances other than thermo-oxidative degradation. It is considered reasonable to disregard these positions where the adhesion of the supply line has been so poor in the fixed zone, that it has not been possible to measure it.

4 Other types of failures

To broaden perspectives regarding different types of failures, an international workshop has been held and failure statistics from Swedenergy have been processed.

4.1 WORKSHOP

A workshop was held in April 2023. The aim was to discuss the condition of district heating networks in different countries, compile failure mechanisms other than loss of adhesion in prefabricated district heating pipes, compile methods for status assessments, discuss conditions for accelerated ageing, and compile knowledge about lifetime estimates.

A failure case was presented [12] where the adhesion had failed, the service pipe had expanded longitudinally and compressed the insulation at the bend and a leakage had occurred in the casing at the shrink joint between the straight pipe and the bend. The pipe was just over 20 years old and had had operating temperatures of up to 125 °C and the pipe bend was surrounded by cushions. A possible failure scenario is that water had leaked in via the shrink joint, which had become hot when it was insulated with cushions. Mastic in the shrink joint changes properties as the temperature increases and seals less well. The water has led to the insulation being partly destroyed by hydrolysis and the service pipe has been allowed to expand freely and could have caused further damage to the bend and insulation.

Failure mechanisms such as internal corrosion of service pipes caused by oxygen and poor water chemistry are hardly encountered in Sweden today [13]. Corrosion of service pipes from the outside is often related to defects during installation and casing joints. There is also leakage that occurs over time, when casing joints are pulled back and forth as operating temperatures vary and mastic ages in shrink joints. Welding defects in service pipes account for a significant portion of the leakage and failures that occur. Depending on the nature of the welding defect, it can be assessed as non-age-related, which is attributed to errors during installation. There is also age-related leakage that is due to crack growth initiated by minor welding defects in the service pipe joints.

Regarding status assessment, PipeOpsy™ was presented, see Chapter 2, and a method based on Thermogravimetric Analysis (TGA) [14]. In accelerated ageing, processes that occur during natural use should be accelerated. The degradation processes during accelerated ageing should not differ from those during natural use, since other types of processes give incorrect results regarding expected lifetime. Experiments at RISE have shown that accelerated ageing of polyurethane as insulation in district heating pipes works up to 140 °C [15]. When it comes to service life estimations of district heating pipes, there is reason to develop refined methods.

4.2 FAILURE STATISTICS

The district heating networks in Sweden have a trench length of 23 000 km. Of this length, 45 % consists of single prefabricated district heating pipes manufactured according to EN 253, with steel service pipes, polyurethane insulation and polyethylene casing. Furthermore, 26 % consists of prefabricated twin pipes of the same materials. Regarding single prefabricated district heating pipes, 142 defects have occurred that have been assessed as age-related during the period 2012-2023 and have been reported to the Swedenergy [16]. It is assumed that many more failure cases exist but have not been reported.

About 75 % of these failures are external leaks, which can be caused by dry mastic or damaged casing joints after many movements in the ground, see Figure 4.1. For 51 % of all age-related failures, the external leaks led to due to corrosion leakage of the service pipes. Other causes of age-related failures and leakage of service pipes can be small pores in weld joints from manufacturing and installation that are exposed to both fatigue and corrosion.

During the period 2012-2023, there have been 150 failures of single prefabricated district heating pipes, which have been assessed as non-age-related. These can be failures that occur due to errors in installation, design and manufacturing of components. In most cases, these errors led to leakage at casing joints or service pipe joints, see Figure 4.2. Together, failures at joints account for 86 % of all non-age-related failures. A small proportion of pipes have failures at positions other than the joints of the casing and service pipes. Other failures may be due to external damage.

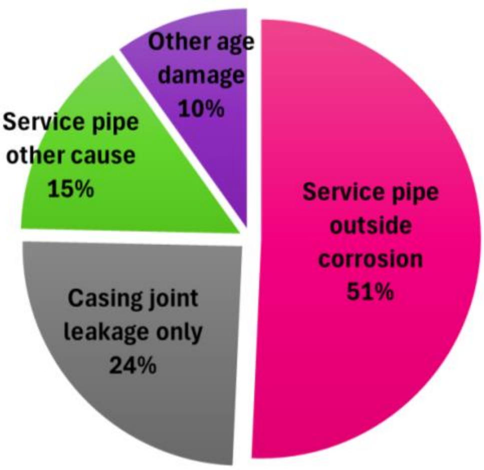

Figure 4.1: Age-related failures for prefabricated single district heating pipes

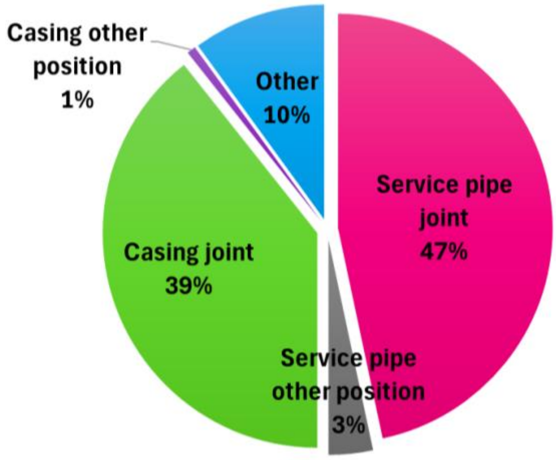

Figure 4.2: Non-age-related failures for prefabricated single district heating pipes

4.3 DISCUSSION

Many failures in prefabricated district heating pipes are related to the joints of the casing or the service pipes. The failure statistics are comprehensive, and no specific time-dependent failure mechanism have been identified, which would argue for the replacement of major parts of the district heating networks.

Today, leaks are repaired as they are detected, which may be sufficient. To prevent leaks, data would be needed which indicate that certain parts require replacement after a certain operating time. Regarding thermo-oxidative degradation and the testing carried out and reported in Chapter 3, these pipes have not yet been subjected to extensive degradation.

It could be as simple as a network owner discovering faults in a certain type of casing joint and fearing further faults in the future. The network owner could then plan to excavate and replace this type of joints along the relevant sections.

5 Conclusions

During the project, 11 paired status measurements on the district heating supply pipelines in the field and further analysis in the laboratory were planned. In each pair, the supply line in one position is located in the fixed zone and in the other in the sliding zone. Two pairs were excluded, one pair being pipes installed at different times and the other due to uncertain information.

A conversion of the operating time with varying operating temperatures to an equivalent operating time at the reference temperature of 95 °C is made. The same damage or degradation is assumed to occur in both cases, but the impact is easier to quantify in the latter case. This makes it easier to compare what different pipelines have been exposed to.

In the cases investigated, the equivalent operating time at the reference temperature of 95 °C is around 20 years. Considering that the requirements in the standard EN 253 [11] for a service life of 30 years at a continuous operating temperature of 120 °C, the tested pipes have been in operation for a relatively short time.

In the chemical analysis, the degradation is greater in the sliding zone than in the fixed zone. With a probability of 97.5 %, the degradation is greater in the sliding zone than in the fixed zone. In some individual cases of the positions examined there is a clear difference between the sliding and fixed zones.

Regarding adhesion, it is somewhat less clear that the deterioration of adhesion is greater in the sliding zone than in the fixed zone. With a probability of 93%, the deterioration of adhesion is greater in the sliding zone than in the fixed zone.

As for other types of failures, these are most often related to joints in the casing or the service pipes. In the event of a fault in the casing joints, groundwater leaks into the district heating pipeline destroying the insulation and rusting the service pipe. In the event of a fault in the joints of the service pipe, hot water leaks out and destroys the insulation. When the water spreads along the pipeline, long stretches of insulation can be destroyed. A large proportion of these failures are not age-related but are due to errors and mistakes in the installation, design or manufacturing of components.

There are many other failures related to joints, which are related to age. Shrink-type casing joints can lead to leakage over time as the mastic dries and seals less well or as the joints are damaged by many movements in the soil. Furthermore, small pores in welded joints in service pipes from manufacturing and installation, which are exposed to both fatigue and corrosion, can lead to leakage over time. Better technical solutions, training of personnel and inspections are estimated to reduce the risk of leakage in newer pipelines.

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Appendix A: Pictures of plugs

Pictures of plugs from field measurements are shown in Table A. 1.

Table A. 1: Pictures of plugs from field measurements

Kabelgatan: Fixed zone flow	Kabelgatan: Sliding zone flow	Kabelgatan: Return
		
Errarpsvägen: Fixed zone flow	Errarpsvägen: Sliding zone flow	Errarpsvägen: Return
		
Huskvarnavägen: Fixed zone flow	Huskvarnavägen: Sliding zone flow	Huskvarnavägen: Return
		

Bergavägen: Fixed zone flow	Bergavägen: Sliding zone flow	Bergavägen: Return
		
Kanalgatan: Fixed zone flow	Kanalgatan: Sliding zone flow	Kanalgatan: Return
		
Ekhagsringen: Fixed zone flow	Ekhagsringen: Sliding zone flow	Ekhagsringen: Return
		

Hermansvägen: Fixed zone flow	Hermansvägen: Sliding zone flow	Hermansvägen: Return
		
Södra Jordbro: Fixed zone flow		Södra Jordbro: Return
		
	Jordbro v.v.: Sliding zone flow	Jordbro v.v.: Return
		

Ölandsgatan: Fixed zone flow	Ölandsgatan: Sliding zone flow	Ölandsgatan: Return
		
Ristippen: Fixed zone flow	Ristippen: Sliding zone flow	Ristippen: Return
		
Lantmätarvägen: Fixed zone flow	Lantmätarvägen: Sliding zone flow	Lantmätarvägen: Return
		

EFFECTS OF MECHANICAL LOADS ON AGEING OF PREFABRICATED DISTRICT HEATING PIPES

Degradation of polyurethane and deterioration of adhesion in prefabricated district heating pipes is assessed to be greater in the sliding zone than in the fixed zone. Precisely in the sliding zone the adhesion needs to be good. In the cases investigated, no extensive deterioration of the district heating pipes has yet occurred. Other types of failures than loss of adhesion are often related to joints in the casing and service pipes. For joints, some failures are assessed to be age-related and others not.

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