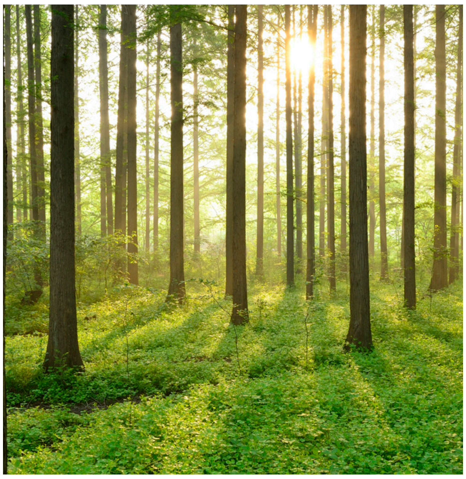
LIFETIME PREDICTIONS AND STATUS ASSESSMENTS OF DISTRICT HEATING PIPELINES

REPORT 2022:872



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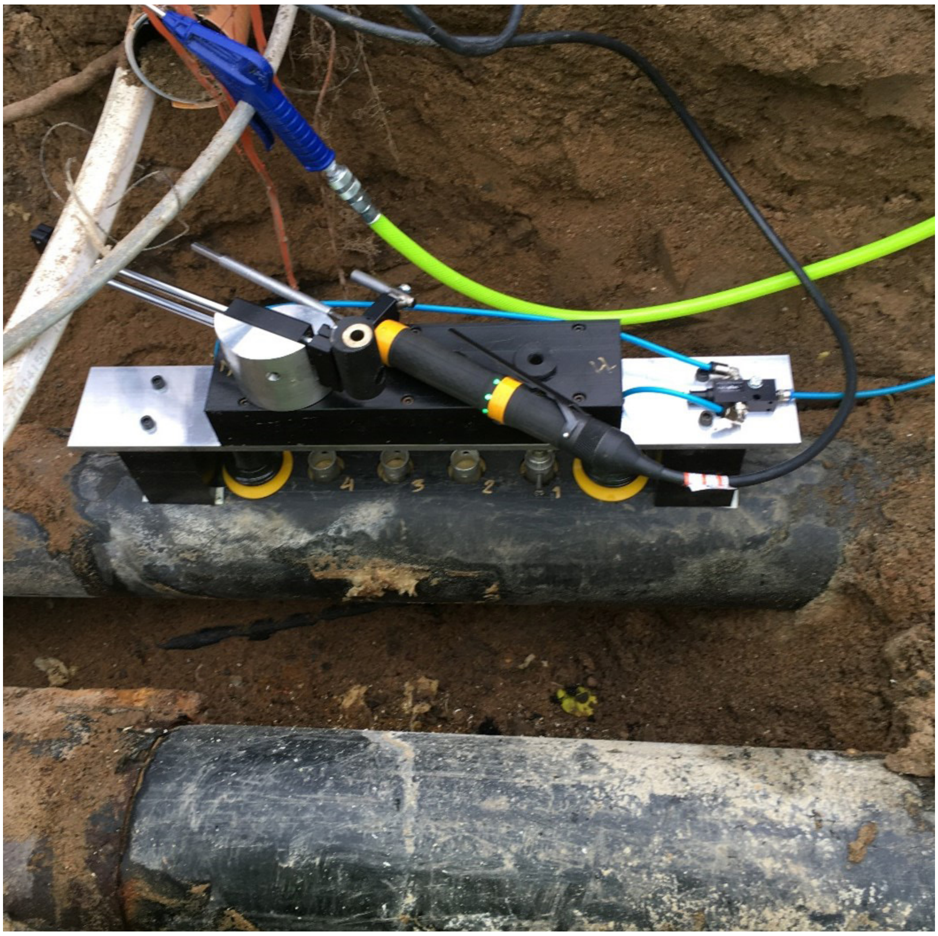

Energiforsk

Lifetime predictions and status assessments of district heating pipelines

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ISBN 978-91-7673-872-6 | © Energiforsk juni 2022
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Foreword

One way to cost-effectively maintain district heating networks is to selectively replace the pipes that are in need of maintenance which requires knowledge of the status of the pipe. This project aimed to develop a field method for measuring the functional status of district heating pipes in operation. The project has also aimed to develop an internationally accepted methodology for life time expectancy with regard to lost adhesion between insulation and pipe.

The project was led and conducted by Jan Henrik Sällström together with colleagues Ignacy Jakubowicz, Alberto Vega och Nazdaneh Yarahmadi from RISE Research Institute of Sweden.

A reference group consisting of Magnus Ohlsson, Öresundskraft (chair); Daniel Byström, Skellefteå Kraft; Josefin Ekman, E.ON Energiinfrastruktur; Shahriar Badiei och Gun Bjurling, Vattenfall; Lennart Kramér, Göteborg Energi; Martin Linder, Tekniska Verken i Linköping; Johan Lundén and Linda Mårtensson, Kraftringen has followed the project and assured the quality and the usability of the results.

The project is part of the FutureHeat program, with the long-term goal to contribute to the vision of a sustainable heating system with successful companies that utilize new technological opportunities and where the investments made in district heating and cooling are utilized to the best of their ability. This project is part of the second phase of the program.

The FutureHeat program is led by a steering committee consisting of Jonas Cognell, Göteborg Energi (chair); Anders Moritz, Tekniska verken i Linköping; Anna Hinderson, Vattenfall AB; Charlotte Tengborg, E.ON Värme Sverige; Fabian Levihn, Stockholm Exergi; Holger Feurstein, Kraftringen; Patrik Grönbeck, Borlänge Energi; Leif Bodinson, Söderenergi; Lena Olsson Ingvarson, Mölndal Energi; Magnus Ohlsson, Öresundskraft; Niklas Lindmark, Gävle Energi; Per Örvind, Eskilstuna Strängnäs Energi & Miljö; Petra Nilsson, Växjö Energi; Staffan Stymne, Norrenergi; Stefan Hjärtstam, Borås Energi och Miljö; Svante Carlsson, Skellefteå Kraft; Ulf Lindquist, Jämtkraft and Julia Kuylenstierna (co-opt), Energiforsk. Deputies have consisted of Ann Britt Larssson, Tekniska verken i Linköping and Peter Rosenkvist, Gävle Energi.

Julia Kuylenstierna

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

Summary

The project has focused on district heating pipes built up of steel service pipes, polyurethane insulation (PUR) and polyethylene casing. The project had two main objectives: A field method should be developed to measure the functional status of district heating pipes in operation and an internationally accepted methodology for lifetime prediction regarding loss of adhesion would be presented.

Even if existing systems are expanded, modernized, and operated differently in the future, there is an interest in continuing to use old district heating pipes for as long as possible. Old pipelines need to be maintained in a cost-effective way through a planned and selective replacement.

A field method (RISE plug method) to assess the status of district heating pipes in operation has been developed in the project. The method measures the adhesion strength (shear strength) between insulation and service pipes. The field method has been supplemented with a chemical analysis of removed insulation after testing in the laboratory. A restoration method where removed insulation is replaced, and the casing is sealed after testing has also been developed. The RISE Plug method, the chemical analysis and the restoration method form a complete method called PipeOpsy. The method's robustness and reliability have been verified with many measurements in the field as well as supplementary tests in the laboratory.

A method to compare service time at a selected reference temperature for different district heating pipelines after use has been presented. A limit for acceptable axial shear strength has been proposed to 0,040 MPa, which can be used in an initial assessment. A specific value for the current conditions can be determined based on the dimension of the pipe, laying depth and the friction between the casing and the filling material. The district heating pipes analysed in the project generally had, with a few exceptions, a sufficiently good status for continued operation. Most of the pipes were also not considered to have been exposed to a high operating temperature for many years. Two of the pipelines had service times of about 30 years at the reference temperature of 95 ° C. The other nine had significantly lower service times at the same temperature. Additional measurement results from laboratory measurements have been included as a comparison, and among these, two pipes had been exposed to accelerated ageing corresponding to 44 and 56 years, respectively.

About methodology for lifetime prediction, the research situation has been determined through a literature review. Two workshops have been conducted. A reasonable temperature level for accelerated testing has been agreed. A platform for international continued collaboration has been created together with others within the IEA DHC for research on lifetime prediction of pre-insulated district heating pipes.

Sammanfattning

Livslängdsprediktering och statusutvärdering av fjärrvärmeledningar

Projektet har fokuserat på fjärrvärmeledningar uppbyggda av medierör av stål, isolering av polyuretan (PUR) och mantel av polyeten. Projektet hade två huvudmål: En fältmetod skulle utvecklas för att mäta den funktionella statusen hos fjärrvärmeledningar i drift och en internationellt accepterad metodik för livslängdsprediktering med avseende på förlorad vidhäftning skulle presenteras.

Även om befintliga system byggs ut, moderniseras och driftas annorlunda i framtiden finns det ett intresse av att fortsätta använda gamla fjärrvärmeledningar så länge som möjligt. Gamla ledningar behöver underhållas på ett kostnadseffektivt sätt genom ett planerat och selektivt utbyte.

En fältmetod (RISE pluggmetod) att bedöma status hos fjärrvärmeledning i drift har utvecklats i projektet. Metoden mäter vidhäftningsstyrkan (skjuvhållfasthet) mellan isolering och medierör. Fältmetoden har kompletterats med en kemisk analys av borttagen isolering efter provning i laboratoriet. En återställningsmetod där borttagen isolering ersätts och manteln tätas efter provning har också utvecklats. RISE Pluggmetod, kemisk analys och återställningsmetoden utgör en komplett metod som kallas PipeOpsy. Metodens robusthet och tillförlitlighet har verifierats med stort antal mätningar i fält samt kompletterande tester i laboratoriet.

En metod att jämföra driftstid vid en vald referenstemperatur för olika fjärrvärmeledningar efter användning har presenterats. En gräns för godtagbar axiell skjuvhållfasthet har föreslagits till 0,040 MPa, som kan användas vid en första bedömning. Ett specifikt värde för de aktuella förhållandena kan bestämmas utgående ifrån ledningens dimension, läggningsdjup och friktion mellan mantel och fyllnadsmaterial. De i projektet analyserade fjärrvärmeledningarna hade generellt sett, med enstaka undantag, en tillräckligt bra status för fortsatt drift. Flertalet av ledningarna bedömdes heller inte ha utsatts för en hög driftstemperatur under många år. Två av ledningarna hade en driftstid på knappt respektive drygt 30 år vid referenstemperaturen 95 °C. De övriga nio hade väsentligt kortare driftstid vid samma temperatur. Ytterligare mätresultat från laboratoriemätningar har tagits med som jämförelse, och bland dessa hade två rör utsatts för accelererad åldring motsvarande 44 respektive 56 år.

Vad gäller metodik för livslängdsprediktering har forskningsläget fastställts genom en litteraturöversikt. Två workshops har genomförts. En rimlig temperaturnivå för accelererad provning har överenskommits. En plattform för internationell fortsatt samverkan har skapats tillsammans med andra inom IEA DHC för fortsatt forskning om metodik för livslängdsprediktering hos förisolerade fjärrvärmeledningar.

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1 Introduction

Even if existing systems are expanded, modernized, and operated differently in the future, there is an interest in continuing to use old district heating pipes for as long as possible. Old pipelines need to be maintained in a cost-effective way through a planned and selective replacement.

The project has focused on district heating pipes built up of steel service pipes, polyurethane insulation (PUR) and polyethylene casing. The project had two main objectives: A field method should be developed to measure the adhesion strength of district heating pipes in operation and an internationally accepted methodology for lifetime prediction regarding loss of adhesion should be presented.

Loss of adhesion between insulation and service pipes is assessed to be the most important failure mechanism because when the adhesion strength (shear strength) is lost, moving steel service pipes close to bends can be subjected to fatigue and break. Furthermore, the insulation in the bends can be compressed and broken by the service pipe, which can lead to damage to the casing and its joints. Movements and fatigue are due to temperature fluctuations in the district heating systems during operation. When leaks in service pipes and casing pipes occur, long distances of the insulation can be destroyed due to contact with hot water. Furthermore, the water will lead to corrosion of the service pipe.

A field method (RISE plug method) to assess the status of district heating pipes in operation is developed in the project. The method measures the adhesion strength (shear strength) between insulation and service pipes. Its measurement accuracy and the correlation with axial shear strength are studied. The temperature dependence of the shear strength is also studied since the properties of the insulation can vary with the temperature.

A restoration method where removed insulation is replaced, and the casing is sealed after testing is also developed. The field method is supplemented with a chemical analysis of removed insulation in the laboratory. The whole process with the RISE Plug method, the chemical analysis and the restoration method form a complete method called PipeOpsy. The method's robustness and reliability are verified with many measurements in the field as well as supplementary tests in the laboratory.

Furthermore, the goal is, through international collaboration with other actors in district heating sector, to make an analysis of the research and create a platform to achieve consensus regarding methods for life expectancy assessment of district heating pipelines. An important part is to be able to predict how the adhesion strength changes over time because of the degradation of the polyurethane insulation under different operating conditions. Through collaboration with others within the IEA DHC, a platform is built to collaborate and start new international projects, which lead to better use of resources and maintenance priorities in this area.

The final goal is to be able to predict the remaining service life by combining results from field measurements of adhesion strength and chemical analysis (called PipeOpsy) with an accepted calculation model.

2 Literature survey

Prefabricated district heating pipes, consisting of a casing of polyethylene (HDPE), insulation of polyurethane and service pipes of steel, degrade and deteriorate over time. In this report, deterioration of the insulation and its adhesion to the service pipe is studied.

Corrosion of service pipes, which is limited by the presence of additives in the circulating water, is not treated. Deterioration of the casing of the pipelines or the tightness of joints are also not addressed. The main degradation mechanisms leading to degradation of polyurethane insulation are:

- Thermal degradation: At high temperatures the polyurethane degrades when bonds in the molecules break. The polyurethane then has deteriorated mechanical properties.
- Thermo-oxidative degradation: Oxygen diffuses into the insulation and reacts with the polyurethane. The insulation is coloured brown and has deteriorated mechanical properties.
- Mechanical-chemical degradation: Mechanical loading on a polymeric material accelerates the degradation of the material, often due to morphological changes in the material caused by the stress.
- Diffusion of gases: Air (nitrogen and oxygen) diffuses in through the casing and carbon dioxide diffuses out. The blowing gas (cyclopentane or CFC11) also diffuses out of the insulation. In the first case, the casing is the protective barrier and in the second case, the insulation itself is the barrier.

The polymerization reaction can also go in the opposite direction, but this happens only at very high temperatures, as Schuricht & Leuteritz (2010) reported. This does not happen during normal use of the pipelines. Jiao *et al.* (2013) investigated thermal degradation of polyurethane in oxygen and nitrogen environments with thermogravimetric analysis (TGA), differential scanning calorimetry (DSC) and IR spectroscopy. The degradation in an oxygen environment was faster than that in nitrogen and the decomposition of the urethane groups into isocyanate and polyol begins at 200 °C in a nitrogen environment.

The diffusion of gases in district heating pipes and its long-term impact on the insulation capacity has been studied in several works, see *e.g.*, articles by Olsson *et al*. (2001, 2002) and the dissertation by Persson (2015). Olsson studied the diffusion of gases through the casing and into the polyurethane. The casing is a diffusion barrier for carbon dioxide, oxygen, and nitrogen, while the polyurethane foam is a diffusion barrier for cyclopentane. Larsen *et al*. (2009) studied differences between unimodal and bimodal type polyethylene casings.

Nolte (1982) investigated the thermal ageing of polyurethane in district heating pipes. Furthermore, the goal was to develop test methods to find out the thermal ageing of polyurethane. Various experiments were performed on polyurethane which was stored and thermally aged in bottles without oxygen supply. Attempts were also made with access to oxygen. The insulation was evaluated with different types of mechanical tests. At accelerated ageing, the temperature was raised to 140, 150 and 165 °C. Nolte estimated that the examined insulation would have a service life of 30 years when the operating temperature was 125 °C. A standard for district heating pipelines was developed with methods for lifetime prediction based on Nolte's ideas, see EN 253 (2009). In the standard, the activation energy 150 kJ/mol was used to calculate the service life.

New studies on the degradation of district heating pipes first started in Germany and were ongoing in various national projects between 2005-2016, see the report by Schleyer & Richter (2016). They feared that the degradation of the district heating pipes could go faster than the prediction methods in the standard EN 253 (2009) showed, see also the paper by Meigen & Schuricht (2005). The purpose was to investigate the effect of oxygen on the ageing process. Both naturally aged and accelerated aged pipes were examined. Experiments have in some cases been performed in an environment with elevated temperature to accelerate the oxygen diffusion through the casing. Very high temperatures up to 190 °C of the service pipe have been used to accelerate the degradation. An apparent activation energy of 95 kJ/mol was determined from experiments at temperatures between 150-190 °C in service pipes with a thin casing (polyethylene film) according to Leuteritz *et al*. (2016).

A new method for determining the status of district heating pipes was developed by Sällström *et al*. (2012, 2013). The method has been further developed within this project and better adapted to be used in the field. It is called the RISE plug method and is described in Chapter 4. The method has been used in several recent projects. Yarahmadi and Sällström (2014) used the method and other conventional methods when studying the ageing of district heating pipes. To accelerate the supply of oxygen, a thinner casing and elevated ambient temperature were used. They also used elevated temperatures of the service pipes at accelerated ageing between 130-150 °C.

Vega et al. (2017) investigated the degradation of polyurethane in the air and nitrogen environment. The polyurethane changed much more in air than in nitrogen, which indicates the importance of thermo-oxidative degradation of the insulation in district heating pipes. Changes of the molecular structure were observed only during thermo-oxidative degradation in air. Vega *et al*. (2018) examined accelerated ageing at 130, 150 and 170 °C and discovered that the behaviour of degradation at the higher temperatures differs from that what occurs at 130 °C. There are other degradation reactions at the higher temperatures 150 and 170 °C than those occurring during normal operation of the district heating pipes. It is therefore not possible to accelerate ageing that occurs during normal operation with temperatures as high as 150 °C. Differences in degradation were observed for shear strength (adhesion), thermal conductivity and changes in the molecular structure.

Celina *et al*. (2005) studied results of accelerated ageing from the literature. Degradation behaviour that does not follow Arrhenius' relationship was explained by two competing processes with different activation energies, which are dominant in different temperature ranges. Vega *et al*. (2020a) concluded that initial changes in the adhesion strength of district heating pipes in use stop after a short time and their status is thereafter at a constant level for a very long time.

Vega *et al*. (2020b) have also investigated the ageing of district heating pipes at elevated temperatures (130 and 140 °C) without and with the influence of axial shear stresses. The district heating pipelines are exposed to shear stresses in the sliding zones when the pipelines slide relative to the ground when the operating temperatures vary. It is essential for the continued function of the pipelines that the adhesion between the service pipe and the insulation remains. Degradation was much faster in the experiments in which the shear stress varied cyclically over time than when it was constantly zero. Variation in adhesion and molecular structure was examined, using FTIR (Fourier Transform Infra-Red) spectroscopy for the latter.

3 Lifetime limitations

There can be various reasons why a part of a pipeline needs to be replaced. There may be leakage of water from a leaky service pipe or a leaky casing, leading to degradation of the insulation and corrosion of the steel service pipe. The leakage may be due to mistakes in the design, installation procedure or external damage to the pipeline. The insulation can also degrade after too high operating temperatures or after normal use at high operating temperatures for a long time.

The highest temperatures are at the service pipe, which means that degradation reactions of the insulation occur faster here than further away. When the adhesion strength (shear strength) is lost, moving steel service pipes close to bends can be subjected to fatigue and break. Furthermore, the insulation in the bends can be compressed and broken by the service pipe, which can lead to damage to the casing and its joints. The movements and fatigue are due to temperature fluctuations in the district heating systems during operation.

When testing new district heating pipes, there is a requirement in Standard EN 253 (2019) that the shear strength must exceed 0.12 MPa. During operation, the pipelines are loaded in the sliding zones where the axial forces are built up. The shear stress at the service pipe depends on the frictional force along the casing, which in turn depends on the coefficient of friction between the casing and the filling material and the pressure between the casing and the filling material.

The horizontal pressure depends on the soil pressure coefficient K_0, which depends on the internal friction angle φ of the filling material:

$$K_0 = 1 - \sin(\varphi) \tag{1}$$

The friction force per unit length on the pipe can be written

$$F_f = \frac{1 + K_0}{2} \, p_v \, \mu \, \pi \, D_c \tag{2}$$

This includes the vertical pressure p_v from the filling material, the coefficient of friction μ between the casing and the filling material and the outer diameter D_c of the casing. Equation (2) is a simplification compared to what is stated in EN 13 941-1 (2019). The shear stress at the service pipe becomes

$$\tau_{sp} = \frac{F_f}{\pi \, D_{sp}} \tag{3}$$

This includes the outer diameter D_{sp} of the service pipe. The coefficient of friction between casing and filling material varies depending on the composition of the material. Molin *et al*. (1997) made measurements of tensile forces when district heating pipes were laid and pulled axially in different filling materials. The coefficients of friction were calculated and were slightly higher than expected, which was explained by the fact that the filling material was extremely well packed. Coefficients of friction from that survey and from the standard EN 13941-1 (2019) are given in Table 1.

Table 1: Friction between casing and filling material

Filling material	Referens	μ
Crushed stone 0-8 mm	Molin (1997)	0.73
Natural material 0-100 mm	Molin (1997)	1.16
Crushed stone 0-100 mm	Molin (1997)	0.83
Sandy soil	EN 13941–1 (2019)	0.4
Sandy soil at fast movements	EN 13941–1 (2019)	0.6

Table 2: Calculated shear stress at service pipe for weight density 18 kN/m^3

Dimension	H_c [m]	μ	τ_{sp} [MPa]
DN 32/140	0.6	0.7	0.021
DN 32/140	1.0	0.7	0.033
DN 32/140	1.5	0.7	0.049
DN 50/160	0.6	0.7	0.017
DN 50/160	1.0	0.7	0.027
DN 50/160	1.5	0.7	0.040
DN 200/400	0.6	0.7	0.014
DN 200/400	1.0	0.7	0.021
DN 200/400	1.5	0.7	0.029

In Table 2, the shear stress at the service pipe has been calculated at a relatively high coefficient of friction for series 3 pipelines with thick insulation. Different coverage depths have been treated. A lower insulation series and a larger dimension gives lower stresses, since the ratio between the diameter D_c of the casing and the diameter D_{sp} of the service pipe decreases. Based on Table 2, it is assessed that a requirement for shear strength of 0.040 MPa is reasonable and covers most cases, *i.e.*, if the requirement is met, there will be no failures due to the insulation coming off the service pipe.

This requirement can be used in an initial assessment of whether the shear strength of the pipeline is sufficient. Should the pipeline be in poorer condition, a specific requirement for the current situation should be determined based on the pipe's dimension, laying depth and friction between casing and filling material. The requirement is thus based on how much shear stress an external load on the pipeline can cause.

4 Field method

A field method has been developed to investigate the status of pre-insulated district heating pipes consisting of steel service pipes, polyurethane foam insulation and polyethylene casing. The method measures the shear strength (adhesion strength) between the insulation and the service pipe of steel. The method is supplemented with laboratory analysis of changes in the chemical structure of the insulation.

Pre-insulated district heating pipes must be able to withstand shear stresses that arise between insulation and service pipes caused by temperature expansion. The shear stresses are found in sliding zones where the pipelines slide relative to the soil in the vicinity of bends. Good adhesion between insulation and service pipes and between insulation and casing is a prerequisite for long-term performance of pre-insulated district heating pipes. When the adhesion releases along long distances, the steel is subjected to fatigue at bends when large varying stresses arise due to varying operating temperatures. According to the standard EN 253 (2009), the shear strength is measured in either the axial or tangential direction. In the present report an alternative method is described, which can be applied in the field without disturbing the operation.

4.1 THE RISE PLUG METHOD

The method is called the RISE plug method and the principle behind it is based on uncovered plugs (drill cores) of insulation being twisted loose from the service pipe, see Figure 1. Aluminium tubes are glued to the plugs to be able to apply a torque to each plug. The torque and the angle of rotation can be measured when the plug is turned loose at a constant angular velocity.

There may be a fracture between the insulation and the service pipe (adhesion fracture) or a fracture in the insulation itself some distance from the service pipe (cohesion fracture). Different hole saws are used to shape the plugs with the final diameter Ø27 mm. An aluminium tube is glued to the plug. Quick-curing polyurethane adhesive is applied to the inner surface of the tube at one end and pressed onto the plug, so that a gap of approximately 2 mm is formed between the aluminium tube and the service pipe. To get a good statistical basis and a low measurement uncertainty with respect to the average value, testing with about seven plugs is required. The shear strength τ_u [Pa] is calculated from the measured torque M [Nm] and the diameter of the plug d = 0,027 m according to

$$\tau_u = \frac{16\,M}{\pi d^3} \tag{4}$$

4.2 FIELD MEASUREMENTS

For field measurements, a special rig has been developed that allows support and steering for both sample preparation and torque measurement, see Figure 2 and Figure 3. The rig is fixed by supports against the casing and suction cups with negative pressure. A combined torque wrench and sensor, which is supported via an arm linked in the rig, is used in the test. In connection with field measurements, the temperature of the service pipe is also measured to be able to assess its impact on the measurement result.

It may be justified to assess the status of pipelines at times when they are exposed after excavation for some other reason. It may also be justified to excavate pipes for status assessment only if these are suspected of having been exposed to high operating temperatures for a long period of time (several years). It is of particular interest to test parts of the pipelines that are in the sliding zones, as this is where the shear strength is needed and it has been shown that the degradation can go faster here, see the article by Vega *et al*. (2020b). All status assessments can be useful for future maintenance planning.

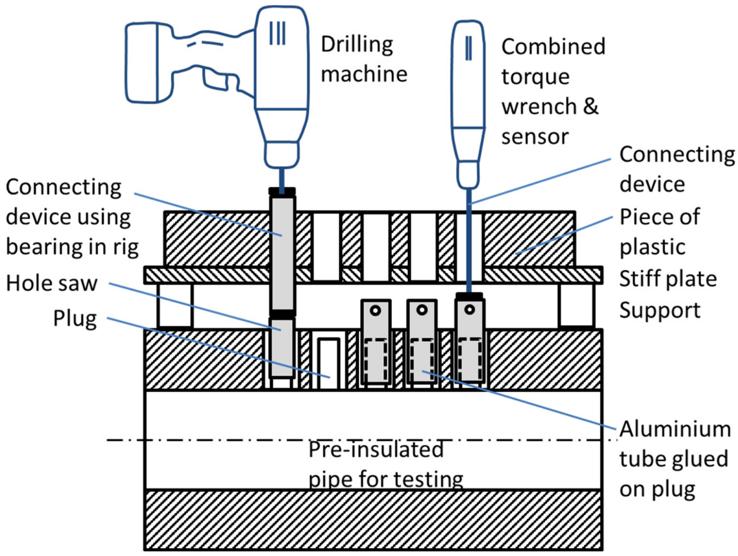

Figure 1: Sketch of RISE plug method

Figure 2: Sample preparation in the field for RISE plug method

Figure 3: Field measurement with RISE plug method

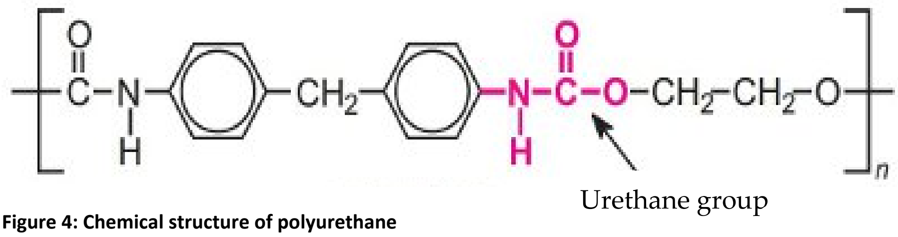

Figure 4: Chemical structure of polyurethane

4.3 CHEMICAL ANALYSIS

To study chemical changes in the molecular structure of polyurethane, an absorption spectroscopy method is used, which in this case is FTIR (Fourier Transform Infra-Red) spectroscopy. An equipment irradiates the material sample with infrared light, and a spectrum is obtained by the wave numbers of the light that are absorbed. The method can be used to identify organic and inorganic materials. It can also be used to study changes in the molecular structure, *e.g.*, as a result of oxidation. To study the degradation of polyurethane as a function of ageing, the spectrum has been normalized with the absorption peak at 1595 cm^{-1}. It represents double bonds between carbon atoms in the aromatic rings, which are thermally stable and not affected by ageing. The degradation is studied by calculating the absorption indices at 1712 cm^{-1} and 1512 cm^{-1}, which represent the urethane bonds C=O and N-H, respectively, after different ageing times at different temperatures, see Figure 4. The absorption index for a certain wave number is defined as the normalized intensity of absorption peak at this wave number.

4.4 MEASUREMENT RESULTS

Many naturally aged pipes have been tested with the RISE plug method in the field during operation. In some cases, the test has taken place in the field when the network has been shut down and in other cases in the laboratory on pipes that have been removed from the district heating network. The measurement results are reported in Table 3. Here, a lower limit of the shear strength is also reported based on the calculated extended measurement uncertainty with two standard deviations and that the measurement results are normally distributed. With 97.5% probability, the actual shear strength is greater than the specified lower limit. This is based on that with 95% confidence, the actual average value of the shear strength is expected to be within the range

$$\tau_{avr,ci} = \tau_{avr} \pm t_{97,5\%,N-1} \times \frac{\tau_{std}}{\sqrt{N}} = \tau_{avr}\left(1 \pm U_\tau\right) \qquad (5)$$

Here, the increased measurement uncertainty is defined as

$$U_\tau = t_{97,5\%,N-1} \times \frac{\tau_{std}}{\tau_{avr}\sqrt{N}} \qquad (6)$$

Here, τ_{avr} is the calculated average value of measurements made and the standard deviation for measurements is τ_{std}. The number of measurements is N and the 97.5% quantile of t-distribution with (N-1) degrees of freedom is denoted $t_{97,5\%,N-1}$.

To reduce the variation of the measurement results, samples have been taken close together along a generatrix. As a rule, 6-7 tests were needed to reduce the average measurement uncertainty to an acceptable level. The measurement results in Table 3 are discussed in Chapter 7 together with results from the chemical analysis.

Table 3: Measurement results for naturally aged district heating pipes. Measurements were performed on site during operation, on site after shutdown and in laboratory. This is evident from temperatures of service pipes during testing. Testing in laboratory takes place at 23 °C, at lower temperatures pipeline is turned off and at higher temperatures pipelines are in operation

Place	Date	Year	Temperature at testing [°C]		Shear strength [MPa]		Measurement uncertainty [%]		Lower limit shear strength [MPa]	
	Testing	Inst.	Flow	Return	Flow	Return	Flow	Return	Flow	Return
Linköping	2019-09-17	1996	6	6	0.58	0.59	24	40	0.44	0.35
Jönköping	2019-10-18	2006	10	10	1.0	0.92	22	27	0.78	0.67
Ängelholm	2019-10-22	1979	78	43	0.64	0.46	13	34	0.56	0.30
Uppsala	2019-11-27	1990	72	47	0.55	0.51	16	20	0.46	0.41
Göteborg	2020-04-12		23	23	0.73	0.35	10	23	0.66	0.27
Göteborg	2020-04-17	1982	23	23	0.71	0.70	24	4.5	0.54	0.67
Göteborg	2020-06-12	1987	78	54	0.72	0.54	8,0	10	0.66	0.49
Göteborg	2020-08-03	1982	67	32	0.71	0.67	46	16	0.38	0.56
Ängelholm	2020-09-17	1980	68	40	0.23	0.56	25	13	0.17	0.49
Göteborg	2021-04-15	1981	23	23	0.50	0.25	17	10	0.42	0.22
Stockholm	2021-06-09	1993	23		0.51		15		0.43	
Lund	2021-06-29	1975	70	40	0.34	0.44	16	16	0.29	0.37
Jönköping	2021-06-30	1983	75	52	0.41	0.56	43	19	0.23	0.45
Jönköping	2021-06-30	1991	67	42	0.60	0.62	2.8	12	0.58	0.55
Lund	2021-11-19	1980	23	23	0.67	1.41	7.1	6.4	0.62	1.32

5 Laboratory investigations

Various laboratory tests have been performed to examine the temperature dependence of the shear strength, the correlation of the RISE plug method with the axial shear strength and the tightness of the pipeline after restoration / repair.

5.1 MATERIAL

In laboratory examinations, both newly manufactured pipes and naturally aged pipes from the field have been used. The new pipes have been manufactured by Powerpipe Systems AB with a discontinuous method through single-piece production.

5.2 TEMPERATURE DEPENDENCE

The purpose was to investigate the effect of the operating temperature on the adhesion strength. In the laboratory investigation, three newly manufactured pre-insulated district heating pipes of dimension DN50 / Ø140 mm with a length of 3.7 m were used. All pipes were cut from one and the same pipe. Two of the pipes have been subjected to accelerated ageing by keeping the service pipe at a constant temperature of 140 °C while the ambient temperature has been 23 ° C. The heating has been accomplished by use of electric current conducted through the service pipe. The accelerated ageing lasted for at least 6 months. The intention was that the degradation process would continue until the status (shear strength) of the pipes had passed an initial phase and reached a plateau phase with a constant level. The plateau phase can last a long time, while there is no change in the status measured with shear strength. However, during this phase, changes have previously been observed by use of chemical analysis of the molecular structure of the insulation according to Vega *et al*. (2018).

5.2.1 Procedures

A virgin district heating pipe and two pipes, which had been subjected to accelerated ageing have been investigated. The RISE plug method has been used to study the temperature dependence of shear strength in both new and aged pipes. Five temperature levels were selected: 23, 60, 80, 100, and 120 °C. The pipes were heated with electric current to the desired level and allowed to stabilize over a period of 1-2 hours. Several samples were taken next to each other on a generatrix along the pipe. It takes about seven tests to get an average value with acceptable measurement uncertainty. A test series with five temperature levels on a specific pipe was done over 1-2 days.

5.2.2 Results

The test results are shown in Figure 5. Three pipes have been tested: one virgin and two after accelerated ageing for 310 and 490 days, respectively. The virgin pipe shows a decreasing tendency of the shear strength with increasing temperature.

The aged pipes do not show any such tendency. It turned out that it was necessary to take more samples than 6-7 pieces to reduce the measurement uncertainty of the average value of the shear strength in the experiments. For the pipe aged 310 days, the measurement uncertainty became high as the number of samples was 6-7 at each temperature. For the other pipes, twice as many tests were performed at each temperature, and a smaller measurement uncertainty was obtained. At each test, the samples were taken close to each other to minimize the effect of density variations of the PUR insulation along the pipe and thus obtain a lower measurement uncertainty. Two measurement series were performed for the two pipes with lower measurement uncertainty. The positions have been chosen differently for the two measurement series, but the results for each temperature have been weighed together. The variations along the pipe are assessed to be of the same order of magnitude as the variation obtained when the test temperature varies.

5.3 CORRELATION OF SHEAR STRENGTH MEASURED WITH THE RISE PLUG METHOD OCH STANDARD METHOD

Several tests have been performed to obtain a correlation between results from the RISE plug method and axial shear strength. The pipes used to study temperature dependence have also been used for the correlation. All tests in this comparison have been performed at the laboratory temperature of 23 °C.

5.3.1 Procedures

The RISE plug method has been used to test pipes, which have aged naturally during use or after accelerated ageing in the laboratory. The test has been performed at a temperature of 23 ± 2 °C. The part of the pipes that was not affected by any previous test was sawn into pieces with a length of 200 mm. At least five test pieces were made for testing the axial shear strength.

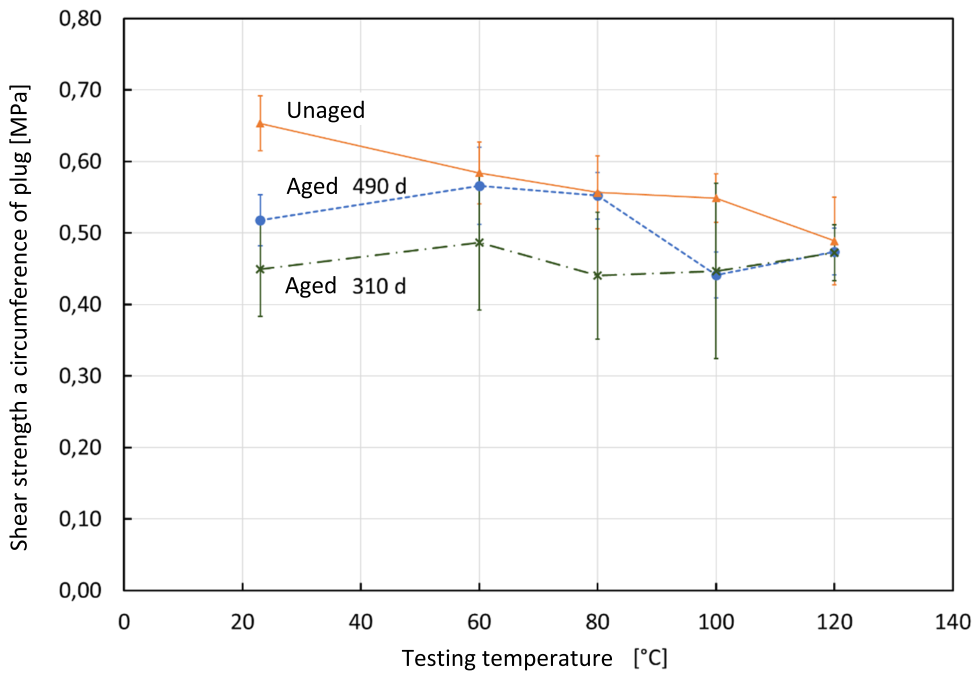

Figure 5: Shear strength for varying temperature for three pipes measured with RISE plug method

Table 4: Results for shear strength measured with RISE plug method and axial method

		Shear strength [MPa] plug		**Measurement uncertainty - plug**		**Shear strength [MPa] axial**		**Measurement uncertainty - axial**		**Quotient**	
Place	Year	Flow	Return	Flow	Return	Flow	Return	Flow	Return	Flow	Return
New pipe	2019	0.69		6.2%		0.30		4.7%		**2.3**	
Kruthusgatan	1982	0.71	0.70	24%	4.5%	0.28	0.20	6.3%	2.9%	2.5	**3.5**
Rondo		0.73	0.35	10%	23%	0.19	0.21	24%	28%	3.8	1.7
Unaged	2020	0.65		5.9%		0.20		17%		3.3	
Aged 310 d	2020	0.45		15%		0.16		8.3%		2.7	
Aged 490 d	2021	0.52		6.9%		0.14		35%		3.7	
Sofierogatan	1981	0.50	0.25	17%	10%	0.13	0.06	20%	13%	3.9	3.9

5.3.2 Results

Shear strength results measured with the RISE plug method and with the axial method are reported in Table 4. The ratio between strength measured with the plug method and the axial method varies slightly. An average value of the ratio weighted with respect to measurement uncertainty is 3.1. An unweighted average of the quotas gives an equivalent result.

5.4 WATER TIGHTNESS OF CASING

After testing with the RISE plug method, the pipe was repaired with prefabricated plugs of polyurethane which were placed into the holes and then polyethylene plugs were welded into the casing. Since it is important that water cannot penetrate the insulation, the restoring method was evaluated by measuring the water tightness of repaired pipes.

5.4.1 Procedures

The ends of the pipe were sealed with silicone. The district heating pipe was placed in a tank with coloured water according to EN 489-1, see Figure 6. The same dyestuff was taken as that used in the district heating systems. The pressure was at least 3 m water column (0.030 MPa) for 24 hours.

Tightness was evaluated by cutting the casing at the plugs afterwards and inspecting it. If water has penetrated, there is dyestuff on the foam. A UV lamp can be used because the colour is fluorescent.

5.4.2 Results

Figure 7 shows the pipe after testing when it was immersed in water with fluorescent paint. The pictures show that no water has penetrated the casing.

Figure 6: Tank used for tightness testing of district heating joints

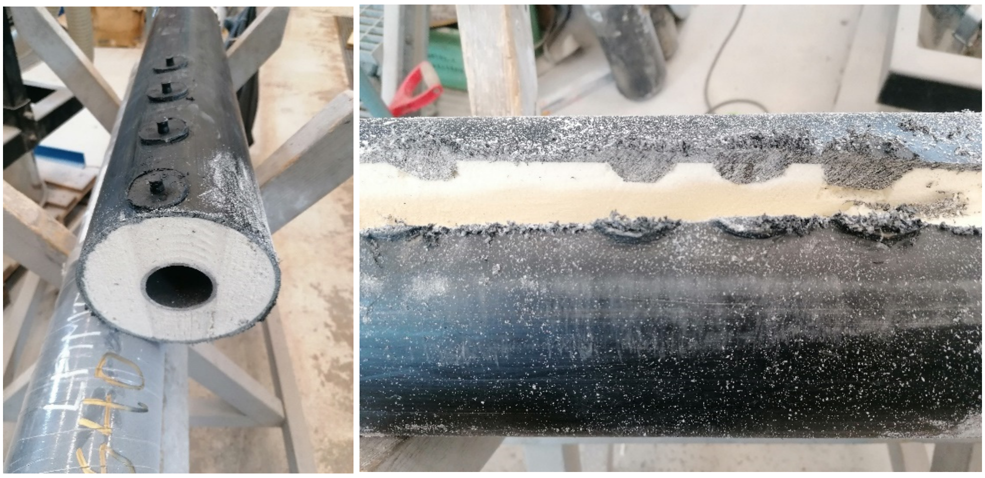

Figure 7: After immersion in water, pipe was sawn apart to see if any water had penetrated

6 Analysis methods

To be able to compare different district heating pipelines with each other which have been exposed to different operating temperatures during different time periods, a method is needed to translate a spectrum of operating temperatures with different service times into a period at a common reference temperature. Furthermore, supplementary analysis methods are needed to study the chemical degradation of the insulation.

6.1 TRANSLATION OF SERVICE TIME AT DIFFERENT TEMPERATURES TO A COMMON REFERENCE TEMPERATURE

District heating networks are usually used at operating temperatures that vary over time and between different systems. To be able to compare the age of pipes from different locations, considering different operating temperatures, we have developed a new calculation method. Periods at different temperature ranges are converted to an equivalent period at a common reference operating temperature as described below.

Let us assume that a chemical reaction follows Arrhenius' equation. Then the temperature dependence of the reaction rate is given of

$$k_i = Ae^{-E_a/RT_i} \tag{7}$$

Here, the velocity constant is k_i at the absolute temperature level T_i. Equation (7) includes the activation energy E_a of the reaction, a pre-exponential factor A and the ideal gas constant R = 8.314 J/(K mol). If we compare the effect of two temperature levels, we can look at the relationship between the velocity constants which gives a measure of the acceleration:

$$\frac{k_1}{k_2} = \exp\left[-\frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \tag{8}$$

Another way is to consider the ratio of the times it takes to achieve a certain state of the material at different temperatures

$$\frac{t_2}{t_1} = \exp\left[-\frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \tag{9}$$

An acceleration factor Af is usually defined based on a temperature increase of 10 K. Assume that

$$T_1 = T_2 + 10K \tag{10}$$

Then Af is defined by

$$\frac{k_1}{k_2} = Af \tag{11}$$

and

$$\frac{t_2}{t_1} = Af \tag{12}$$

As a rule of thumb in chemistry, Af is usually 2 for a temperature difference of 10 K and this is usually referred to as Arrhenius two relationship, which means that the reaction rate of a chemical reaction doubles with an increase in temperature by 10 K.

To compare what different district heating pipelines in the field have been exposed to, we have recalculated temperature spectra to the equivalent times at a certain reference temperature. This translation is illustrated in Figure 8. Here, the acceleration factor Af has been assumed to be 2. The time at the reference temperature then becomes twice, if the actual service time is at a 10 K higher temperature. Table 5 gives a comparison of acceleration factors and activation energy at a certain reference temperature. Case II with the acceleration factor 2.5 has been included, as this has been shown to give a better correspondence between the status of district heating pipelines and the service time for different temperatures.

Table 5: Relationship between acceleration factor and activation energy at certain temperatures

Parameter	Notation	Case I		Case II	
	Af	2		2,5	
Reference temperature	T_0	90	°C	90	°C
Temperature increase	ΔT	10	°C	10	°C
Activation energy	E_a	78	kJ/mol	103	kJ/mol

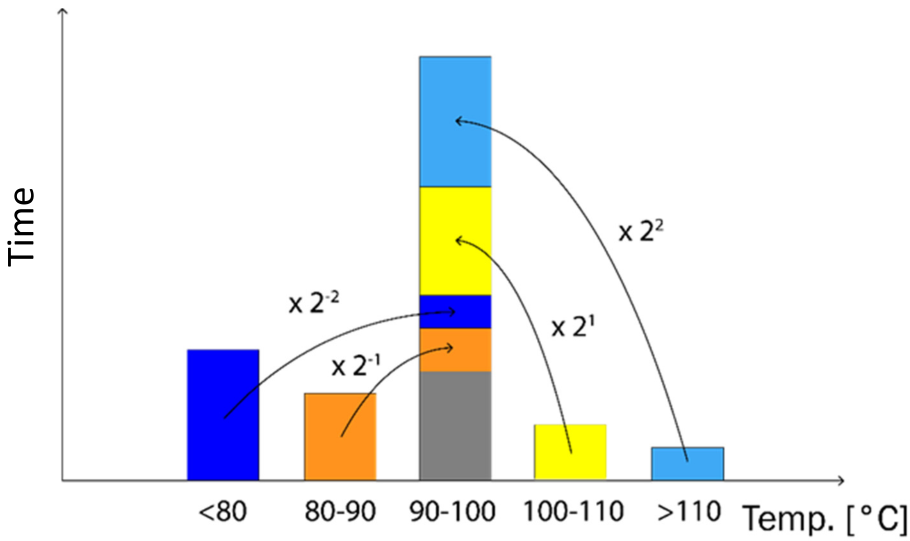

Figure 8: Schematic example for simple conversion of service time at different temperatures, to time at reference temperature if Af is 2

6.2 FTIR ANALYSIS

Degradation of polyurethane usually begins with dissociation of the urethane bonds, see Figure 4 again. To analyse this type of change in the chemical structure of the PUR material because of degradation processes, Fourier Transform Infra-Red spectroscopy (FTIR) with Attenuated Total Reflectance (ATR) has been used. Small material samples 1-2 mm thick, which have been located near the service pipe (2 mm away), were taken from the cylindrical PUR samples from the mechanical tests with the RISE plug method and used in the FTIR analyses. The samples were placed on the ATR crystal and then pressed against the surface to obtain an optimal contact. The obtained spectra were studied in detail to analyse degradation processes as a function of ageing time and temperature.

As a reference, another thin material sample was taken 20 mm from the service pipe. At least three samples were analysed from each position. When IR radiation passes through a sample, some radiation is absorbed by the sample (absorbance) and some passes through (transmittance). The resulting signal at the detector provides an absorption spectrum which is unique to the polyurethane and constitutes a molecular "fingerprint" of the material. Figure 9 shows FTIR spectra of samples taken 2 mm and 20 mm away from the service pipe of an accelerated aged pipeline at 140 °C. Differences in absorbance levels indicate differences in degradation.

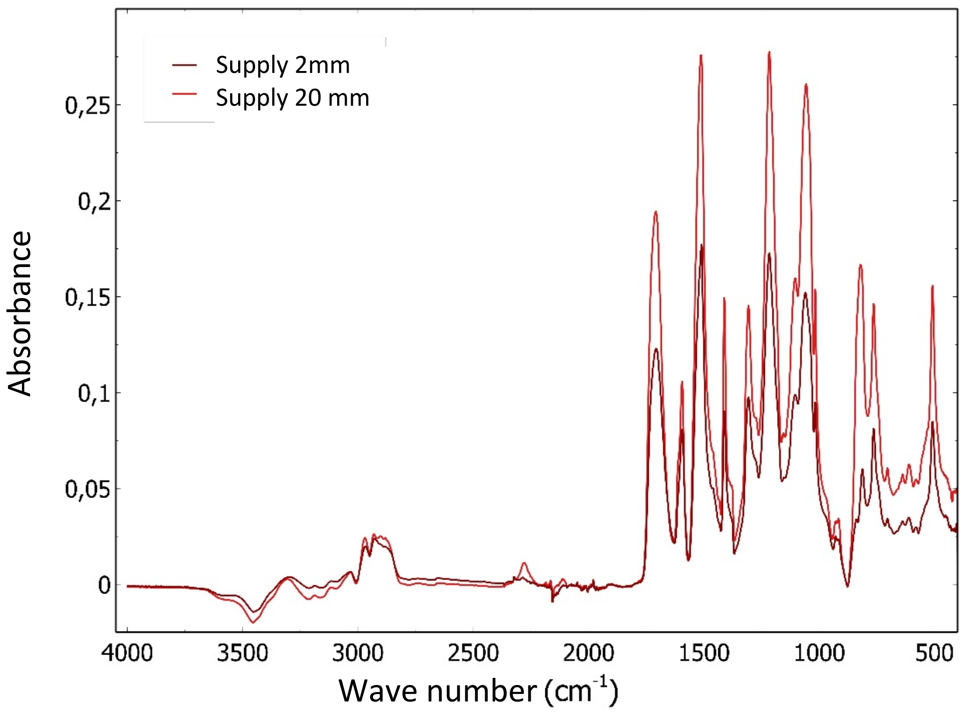

Figure 9: FTIR spectra of samples taken 2 mm and 20 mm from service pipe of accelerated aged pipelines at 140 °C

7 Analysis of results

The results of field measurements are analysed here together with new results of changes in the PUR foam analysed with FTIR.

7.1 MEASUREMENTS OF ADHESION IN THE FIELD

Measurements of shear strength of district heating pipes have been made with the RISE plug method in many places in Sweden, see Table 3. A lower limit for an acceptable axial shear strength has been assessed to be 0.040 MPa, see Chapter 3. The value can be compared with the requirement 0.120 MPa for newly manufactured pipes in EN 253 (2019).

Experimentally, a relationship has been established between axial shear strength and shear strength measured with the RISE Plug Method, see Section 5.3. Here, a ratio between shear strength measured by the RISE Plug Method and the axial shear strength was set to 3.1. Acceptable shear strength measured with the RISE Plug Method will then be 0.124 MPa.

With this background, none of the test sites show too low shear strength, see Table 3 again and Figure 10. In three cases, the margin between measured and permissible value is so small that a more accurate analysis of the pipelines should be made.

This thus applies to a return line from Gothenburg installed in 1981 and the others are supply lines from Ängelholm and Jönköping installed in 1980 and 1983, respecttively. The supply lines from Ängelholm 1980 with the service time 11 years at the reference temperature 95 °C and shear strength 0.23 MPa, and Jönköping 1983 with 36 years and 0.41 MPa. The corresponding lower limits are 0.17 and 0.23 MPa, respectively, when measurement uncertainty is considered. These must be compared with the permissible stress of 0.124 MPa measured with the RISE Plug Method.

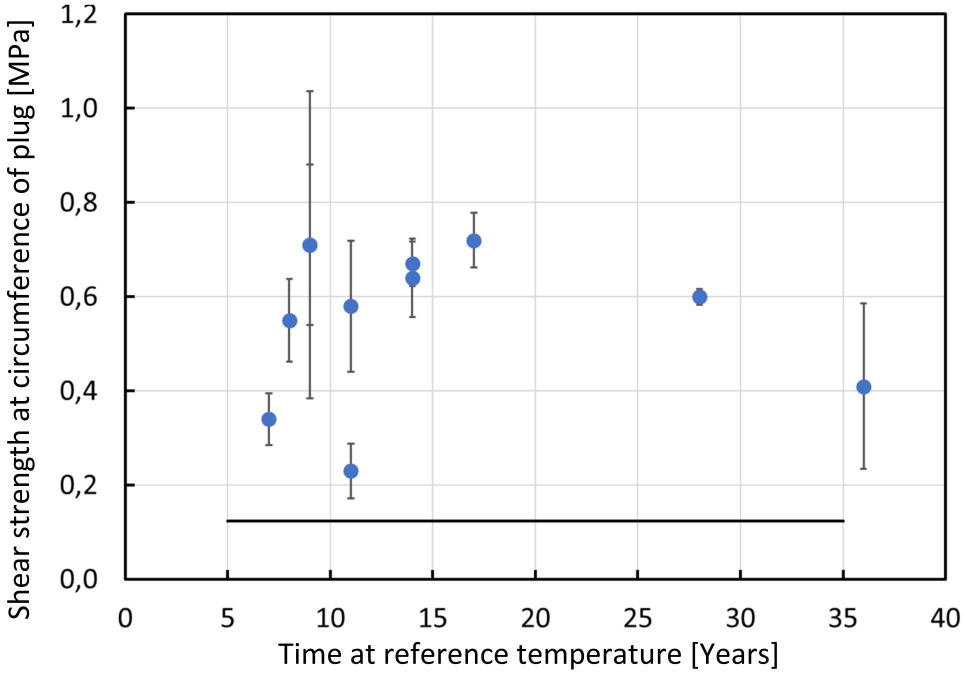

Figure 10: Shear strength in supply pipelines calculated by use of measured torque, as function of recalculated service time at reference temperature 95 °C. Uncertainty in values is marked. Proposal for minimum permissible shear strength marked with black horizontal line

The service time has been recalculated using the method in Section 6.1 to a time at 95 °C. The shear strength is given as a function of the recalculated service time in Figure 10 and in Table 6. The table also contains a corresponding service time at 55 °C for the return lines. In Figure 11, pipelines, which have been tested previously by Vega *et al*. (2020a) in the laboratory are included. In the next step, the shear strength of the return line is used, as a reference for the initial state of the supply line. Figure 12 gives the ratio of the shear strength for supply and return lines, as a function of the recalculated service time of the supply line at 95 °C. The measurement results point to a clearer downward trend than in Figure 11. In Figure 12, we therefore only look at the degradation of the supply line but use the return line as a reference.

Return pipeline from Gothenburg installed in 1981, which was in poor condition, is not included in these diagrams. The supply from Ängelholm installed in 1980 has a comparison time of 11 years and is found in Figure 11 with the level 0.23 MPa and in Figure 12 with 0.41. The supply from Jönköping installed in 1983 has a comparison time of 36 years with the level of 0.41 MPa in Figure 11 and 0.73 in Figure 12.

The results in Figure 12 show that the residual adhesion strength of older pipes is approximately at the same level, between 70 and 90% of the corresponding value for the return pipe, regardless of age. This confirms previous results from accelerated ageing tests, which indicated that the adhesion strength remains constant (referred to as plateau phase) for a very long time (longer than 30 years).

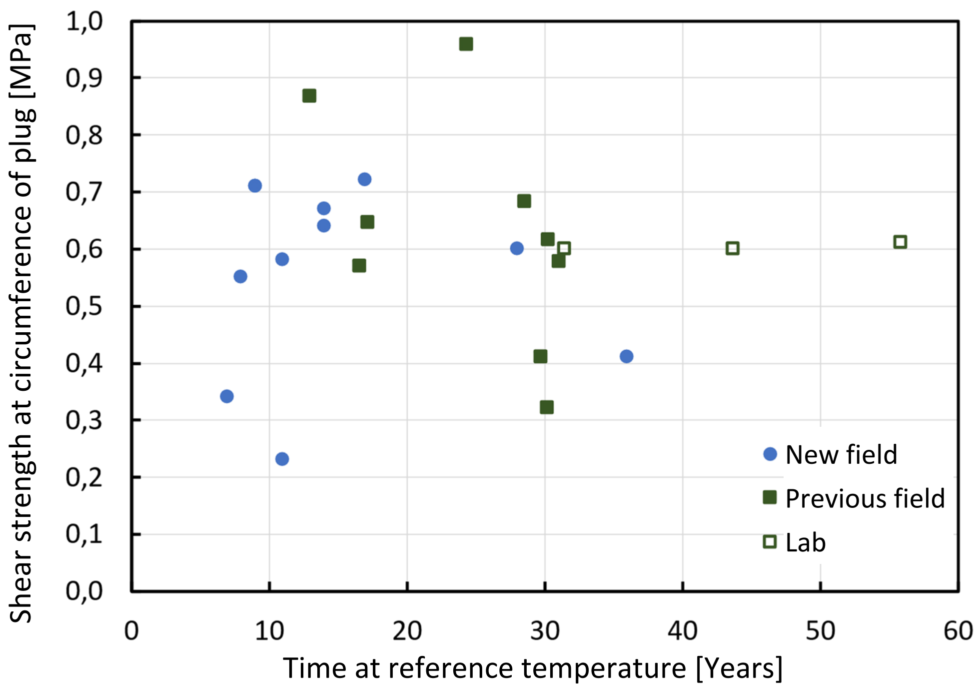

Figure 11: Shear strength in supply lines calculated by use of measured torque, as a function of recalculated service time at reference temperature 95 °C. Previous measurements in laboratory on field samples made by Vega *et al*. (2020a) have been marked with green squares. Previous measurements on pipes aged in the laboratory have been marked with unfilled squares

Table 6: Additional measurement results for naturally aged district heating pipes, see Table 3. Here is service time for selected reference temperatures, shear strength as before and index from FTIR. Index ratios between insulation material taken 2 mm and 20 mm from service pipes are given

Place	Year	Yrs at 95°C	Yrs at 55°C	Strength [MPa]		Case	Index ratio at 1712 cm^{-1}		Index ratio at 1512 cm^{-1}	
		Flow	Return	Flow	Return		Flow	Return	Flow	Return
Linköping	1996	11	4	0.58	0.59	2	0.62	0.99	0.87	0.99
Jönköping	2006			1.00	0.92	2	1.11	0.95	0.98	0.95
Ängelholm	1979	14	20	0.64	0.46	3	0.76	0.91	0.84	0.91
Uppsala	1990	8	8	0.55	0.51	2	0.83	0.94	0.92	0.94
Göteborg				0.73	0.35	3				
Göteborg	1982	9	12	0.71	0.70	2	0.84	0.85	0.84	0.90
Göteborg	1987	17	45	0.72	0.54	3	0.70	0.99	0.66	0.96
Göteborg	1982	9	12	0.71	0.67	2	0.80	0.91	0.81	0.92
Ängelholm	1980	11	16	0.23	0.56	1	0.80	0.93	0.81	0.93
Göteborg	1981	68	272	0.50	0.25	3	0.85	0.63	0.94	0.71
Stockholm	1993			0.51						
Lund	1975	7	3	0.34	0.44	1	0.63	0.91	0.60	0.94
Jönköping	1983	36	27	0.41	0.56	1	0.55	0.86	0.61	0.96
Jönköping	1991	28	22	0.60	0.62	2	0.72	0.73	0.91	0.94
Lund	1980	14	15	0.67	1.41	1	0.70	0.86	0.68	0.96

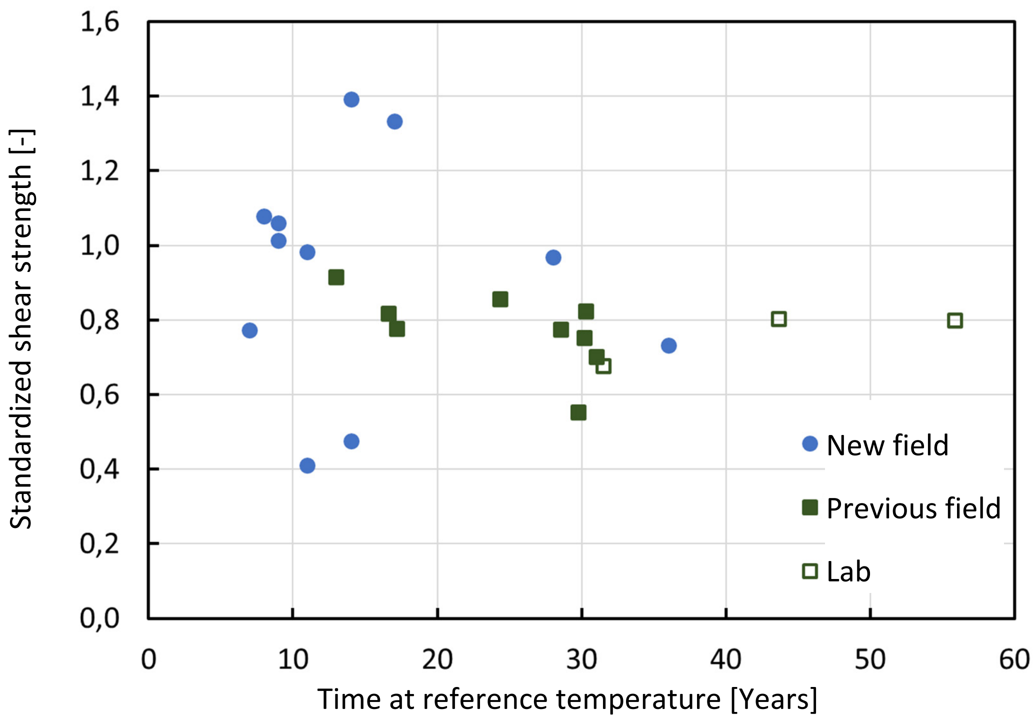

Figure 12: Shear strength in supply lines normalized with shear strength of associated return lines calculated as a function of recalculated service time at reference temperature 95 °C. Previous measurements in laboratory from field samples made by Vega *et al*. (2020a) have been marked with green squares. Previous measurements on pipes aged in the laboratory have been marked with unfilled squares

7.2 FTIR ANALYSIS ON SAMPLES TAKEN FROM FIELD MEASUREMENTS

Polyurethane foam from the supply line and the return line have been analysed separately. The degradation is studied by measuring the absorption index (IR index) at the wave numbers 1712 cm^{-1} and 1512 cm^{-1}, which represent the urethane bonds C=O and N–H, respectively. Foam taken near the service pipe, 2 mm away, and foam taken far from the service pipe, 20 mm away, have been analysed. Ratios between absorption indices for samples taken at these positions from a line are formed for the mentioned wave numbers. For the supply line, the results are shown in Figure 13 and Figure 14. Here, the results are scattered when previous older results have been included. The results that come from the new measurements made in this project show a downward trend with the recalculated service time. Figure 15 and Figure 16 show the corresponding results for the return line. These results show a relatively constant level, which is expected since the return temperatures are significantly lower. The supply line from Ängelholm, which was in poor condition, is found in Figure 13 and Figure 14 at the comparison time 11 years and the levels 0.80 and 0.81 for the wave numbers 1712 and 1512 cm^{-1}, respectively. The supply line from Jönköping is found in Figure 13 and Figure 14 at the comparison time 36 years and the levels 0.55 and 0.61 for the wave numbers 1712 & 1512 cm^{-1}, respectively.

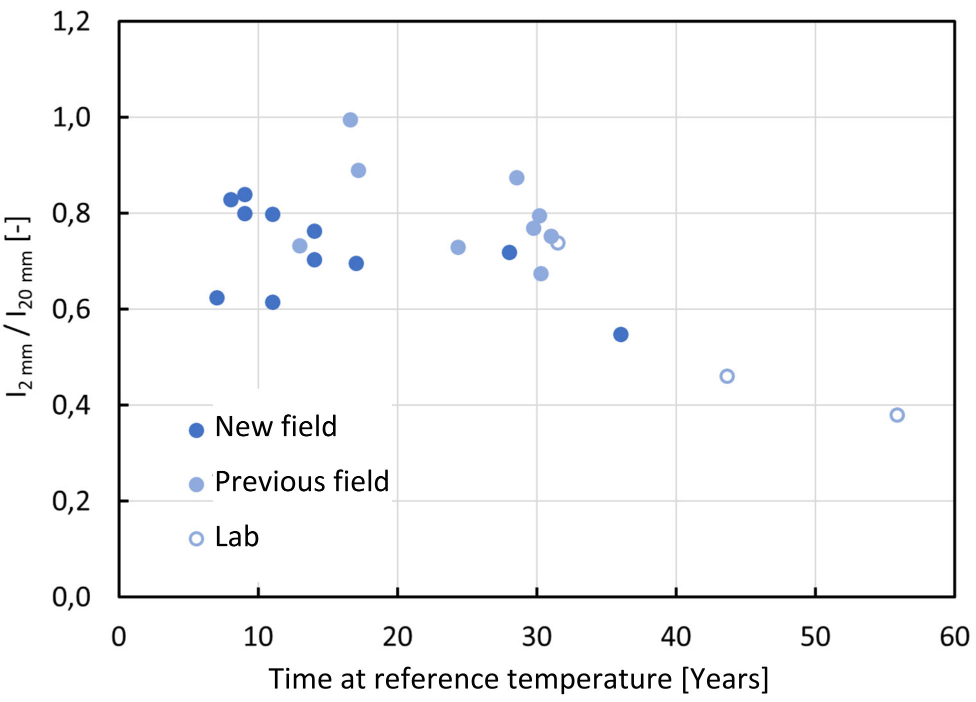

Figure 13: Ratio of absorption index for wave number 1712 cm^{-1} of PUR foam near service pipe (2 mm away) and unaffected foam far from service pipe (20 mm) of investigated supply lines, as a function of recalculated service time at reference temperature 95 °C. Previous measurements from field tests by Vega *et al.* (2020a) have been marked with lighter tone. Previous measurements of pipes aged in laboratory have been marked with unfilled circles

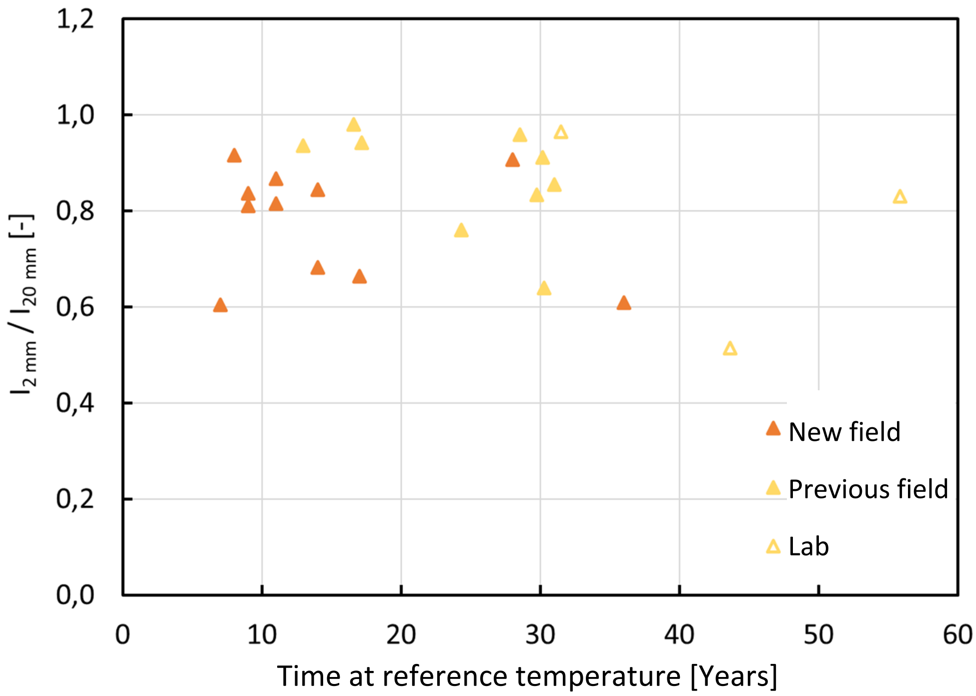

Figure 14: Ratio of absorption index for wave number 1512 cm^{-1} of PUR foam near service pipe (2 mm away) and unaffected foam far from service pipe (20 mm) of investigated supply lines, as function of recalculated service time at reference temperature 95 °C. Previous measurements from field tests by Vega *et al*. (2020a) have been marked with lighter tone. Previous measurements of pipes aged in laboratory have been marked with unfilled triangles

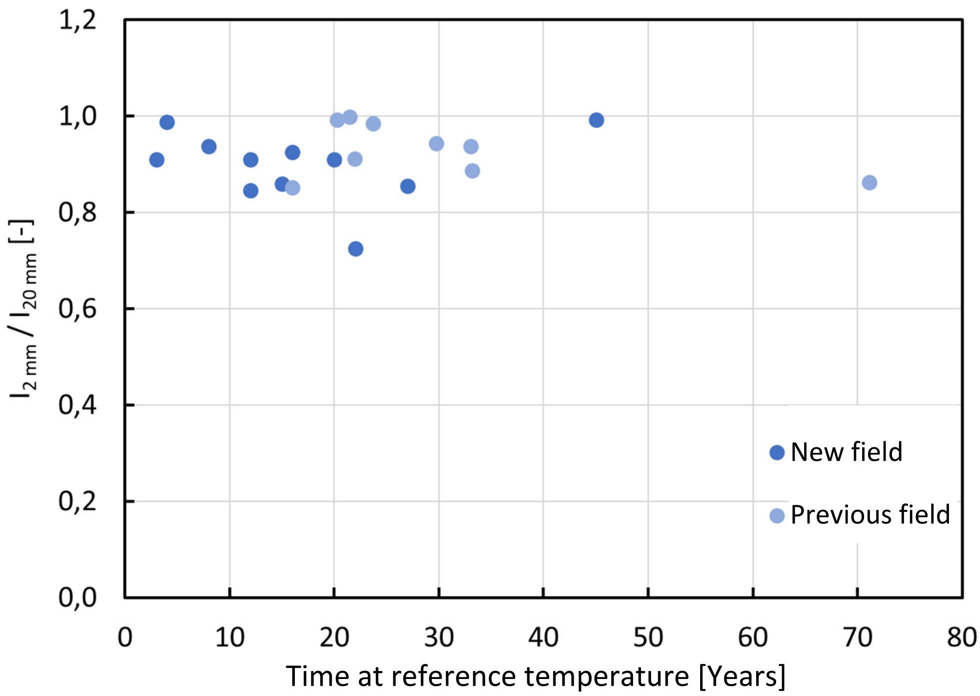

Figure 15: Ratio of absorption index for wave number 1712 cm^{-1} of PUR foam near service pipe (2 mm away) and unaffected foam far from service pipe (20 mm) of investigated return lines, as function of recalculated service time at reference temperature 55 °C. Previous measurements from field tests by Vega *et al*. (2020a) have been marked with lighter tone

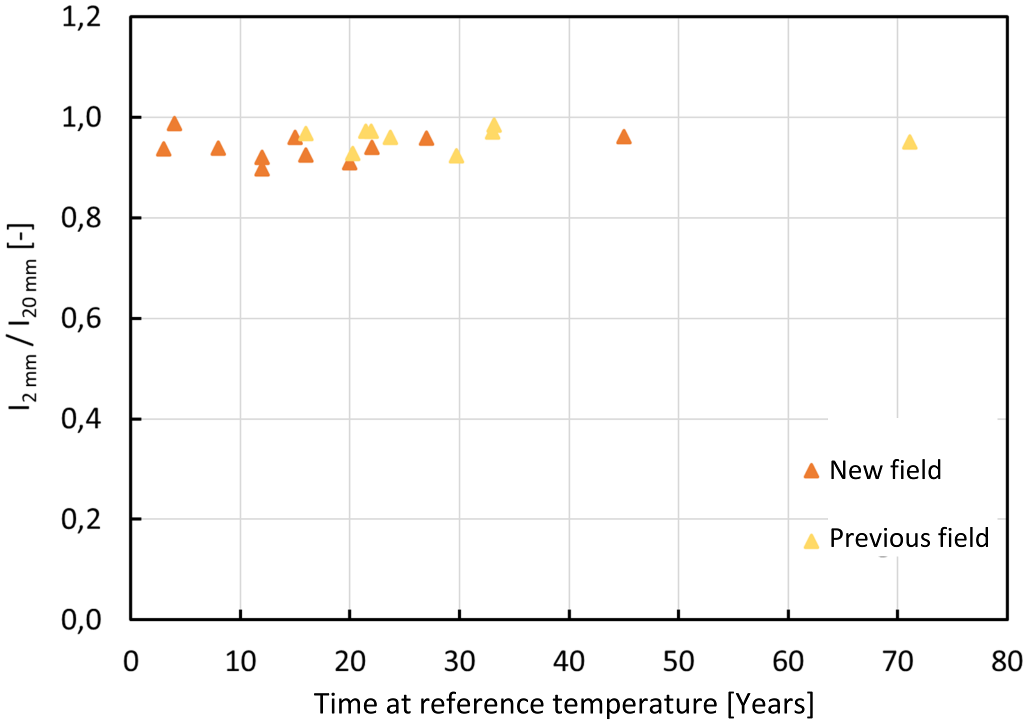

Figure 16: Ratio of absorption index for wave number 1512 cm-1 of PUR foam near service pipe (2 mm away) and unaffected foam far from service pipe (20 mm) of investigated return lines, as function of recalculated service time at reference temperature 55 ° C. Previous measurements from field tests by Vega *et al*. (2020a) have been marked with lighter tone

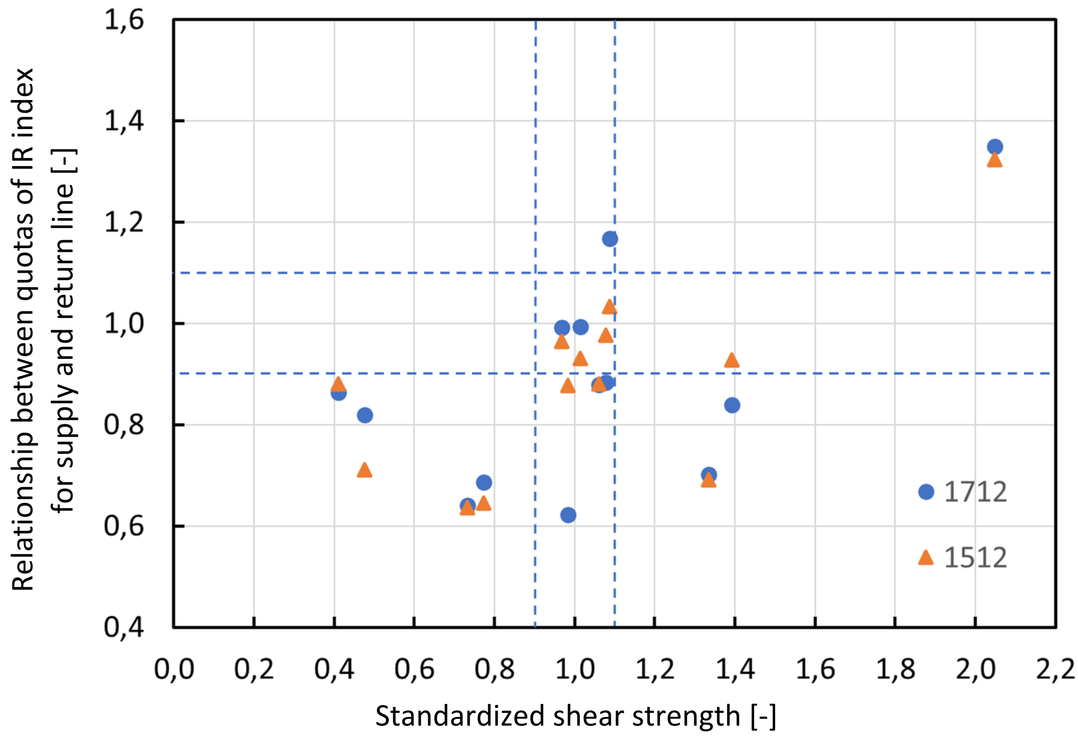

Figure 17: Relationship between quotas of IR index for supply and return line as function of standard shear strength, ie ratio between shear strength (adhesion strength) for supply and return line

7.3 DISCUSSONS

Vega *et al*. (2020a) calculated relative values of the adhesion strength to be able to directly compare values from different naturally aged district heating pipelines. The ratio of the adhesive strength (shear strength) of the supply and return lines was calculated when the return line was considered as a reference. This means that if the ratio is clearly below 1, the supply line has a reduced adhesion strength compared to the return line, see Case 1 in Table 6. If the value is approximately 1, no change has taken place, see Case 2 in Table 6. To find out if reduced adhesion is due to chemical degradation of PUR, we analysed PUR, which was located near the service pipe (2 mm away) with FTIR (see Sections 6.2 and 7.2) by calculating the IR index for peaks at 1712 cm^{-1} and 1512 cm^{-1}, which belong to bonds in the urethane group, see Figure 4. Ratios of IR index for PUR taken 2 mm and 20 mm from the service pipe were formed for each line. The relationship between the quotas for the supply and return line was studied. If the IR ratio is clearly below 1 while the associated adhesion ratio is also below 1, we interpret this as a confirmation that chemical degradation is the cause of the loss of adhesion. The diagram in Figure 17 summarizes the results from naturally aged pipelines listed in Table 3 and Table 6.

It can be seen in the diagram that three pipelines deviate from the expected results in terms of adhesion, see Case 3 in Table 6. The result at the top right is derived from pipelines from "Göteborg 1981" and shows that while the supply line is a bit aged, the return line has a strong reduced adhesion strength. The IR result and ocular inspection also show a significant chemical degradation of the return line. The other two cases that have an adhesion ratio greater than 1.1 while the IR ratios are less than 1. This means that the return line has lower adhesion than the supply line, while the IR results show that there has been no chemical degradation of the return line, but some degradation of the supply. The reason may be that supply and return lines are not produced at the same time or are two different products. Another point falls a little outside with a ratio of adhesive strength of close to 1, even though IR relationship indicate degradation of supply line.

8 International cooperation

Much research has been done on the ageing and status of traditional district heating pipelines with steel service pipes, polyurethane insulation, and polyethylene casing. Various research projects on this have been carried out in Germany between 2004 and 2016, which are reported by Schleyer and Richter (2016). In Sweden, several research projects have been carried out, which deal with shear strength. The first were reported by Sällström *et al*. (2012) and Yarahmadi & Sällström (2014). The work was continued by Vega *et al*. (2018).

The research that was done led to the standard EN 253 (2009) being revised and the relationship test time in the laboratory at elevated temperature and service time at operating temperature was removed in EN 253 (2019). There have been divided opinions on how accelerated tests should be performed and at what temperatures.

The aim is to jointly develop and implement agreed methods for accelerated ageing determination of life expectancy and future status. An important part is to be able to predict how the adhesion strength changes over time because of the degradation of the polyurethane insulation when the pipelines are subjected to different operating conditions.

8.1 WORKSHOP NO 1

A Workshop was held on 2021-04-12 with 16 participants from Denmark, Russia, Great Britain, Sweden, and Germany. The workshop began with a definition of what we mean by the service lifetime of a product. This is the time it takes for a critical property to decrease to a critical level when the product is exposed to a given stress. For traditional prefabricated district heating pipes, the service life requirement is 30 years, the critical property is shear strength, stress is 120 °C and the critical level is 0.12 MPa and 45% of the initial level according to EN253. Various research groups from RISE, IMA (Dresden) and HCU (Hamburg) briefly presented their latest experimental research results.

At the Workshop, the general meaning was that accelerated ageing should be carried out with a reasonable increase in temperature, so that the same kind of degradation reactions take place as in normal use. A maximum temperature should be around 140 °C.

The supply of oxygen must be large enough at the accelerated ageing. One opinion was that the diffusion of oxygen through the casing should also be accelerated or at least considered in accelerated ageing.

A design life of 50 years at an operating temperature of 120 °C with short periods up to 130 °C and single peaks up to 140 ° C was proposed. Test periods of a maximum of 1 year but preferably half a year were discussed.

8.2 WORKSHOP NO 2

A second Workshop was held on 2021-09-14 with 13 participants from Denmark, Russia, Sweden, and Germany. It was a continuation of the previous one and would provide an opportunity for deeper and further discussions.

In the discussions, it emerged that there are applications where district heating pipelines are used at significantly higher operating temperatures than normal. It was questioned whether individual applications with high operating temperatures should govern the requirements for district heating pipelines or whether there should be different requirements for other applications.

Normally district heating pipes are used with maximum levels in the range 90-110 °C with single peaks up to 130 °C. EN 253 (2019) states that the service life shall be 30 years at 120 °C with single peaks of 140 °C for a total of 300 hours per year. If a service life of 50 years is desired, the temperatures must be below 115 °C. During the meeting, it was decided that we should produce a basis for the operating temperatures that are applied.

The temperature histories from Swedish networks that we have had access to during this project show that during the winter period, the supply temperature varies around a level within the range 80-100 °C. The standard deviation for a temperature history in winter is in the range 5-10 °C.

The question of temperature during accelerated tests in the laboratory was raised again. It was pointed out that other degradation mechanisms take place at temperatures above 140 °C than at operating temperatures around 100 °C, see the article by Vega *et al*. (2018). Other types of insulated pipes are needed for high operating temperatures in the vicinity of the temperature, 140 °C, which has been proposed as suitable for accelerating behaviour at 100 °C.

The necessity and possibility of increasing the supply of oxygen to accelerate the ageing process was raised. There are two possibilities to increase the oxygen diffusion through the casing. One is to use a thinner casing and the other is to increase the temperature of the environment and thus the casing. After foaming, there is a pressure between the insulation and the casing and the service pipe. This pressure changes if the casing becomes thinner or the temperature increases. These mechanical changes are suspected to be able to affect the deterioration of adhesion. There are ongoing experiments with oxygen measurement in district heating pipes in an ongoing project, Resource-efficient district heating and district cooling systems, which can shed light on whether there is enough oxygen present without the oxygen diffusion being accelerated through the casing.

Measurements of changes in the molecular structure using IR spectra were discussed. Furthermore, the benefits of varying shear stresses were discussed to mimic what happens to the district heating pipelines in the sliding zones. The general conclusion of the workshop was that the discussions and work must continue in a planned project within IEA DHC.

8.3 PROJECT WITHIN IEA DHC|CHP

Work has begun on shaping an internationally co-financed project (Task Shared 6) for status assessment, degradation, service lifetime predictions, asset management of district heating pipelines. The work has been initiated by AGFW together with HCU and RISE. RISE participates as project and sub-project managers in the development of a total of four work packages in the forthcoming application, which consists of five different work packages.

The work packages consist of status assessment, degradation, service lifetime predictions, asset management and future perspectives of district heating networks. In 2021, a refined project description will be produced. Then participants need to write national applications for funding in early 2022, as there are no funds to apply within the IEA DHC|CHP in this type of project.

8.4 RESULTS

An awareness has been created that accelerated ageing should not be performed at such high temperatures as are applied in EN 253 (2019), as its purpose is to accelerate processes that occur when using the pipes.

At the international level, it has been realized that there is a need for cooperation to develop better methods for status assessment and lifetime prediction. One part of this is to better understand how the degradation processes work. Furthermore, the district heating sector has a need for asset management. An international collaboration has started to sort out these issues.

9 Conclusions

A field method (RISE plug method) to assess the status of district heating pipelines in operation has been developed in this project. The method measures the adhesion strength (shear strength) between insulation and the service pipe. The field method has been supplemented with a chemical analysis of removed insulation in the laboratory. A restoration method where removed insulation is replaced, and the casing is sealed after testing has also been developed. All three parts: measurement of the adhesion strength in combination with sampling, chemical analysis of the sample and restoration has been called Pipeopsy. The robustness and reliability of the method have been verified in several field measurements as well as supplementary tests in the laboratory. A calculation method has been developed to estimate a comparable age of different pipelines, that are not directly based on the year of installation.

An equipment to measure shear strength has been built and verified in the field. The measurement accuracy of the method has been studied and results have been correlated to axial shear strength. Furthermore, the temperature dependence of the shear strength has been studied. The results obtained so far show that for an unaged pipe, the shear strength decreases with increasing test temperature (from 0.65 MPa at 20 °C to 0.50 MPa at 120 °C). For aged pipes, the shear strength appears to be independent of the test temperature and is about 0.50 MPa.

A calculation model has been presented that makes it possible to compare effective service time at a selected reference temperature for district heating pipelines exposed to different operating temperatures. The calculation model is based on Arrhenius' "rule of thumb" and an acceleration factor of 2.5 instead of the usual factor of 2.0. In the comparison, it is considered that the reaction rate of the degrading reactions increases approximately by a factor of 2.5 with each temperature increase of 10 °C. To calculate the service time at a selected reference temperature, a representative temperature history for at least one year is required.

For the supply line, 95 °C has been chosen as the reference temperature and for the return line 55 °C. These temperatures and associated service time can be related to the service life being 30 years at 120 °C with single peaks of 140 °C for a total of 300 hours per year according to EN 253 (2019). The calculation model can be used as a tool by network owners to find out which pipelines have aged the most. This in turn can be an important piece of the puzzle for status assessment of existing pipes and maintenance planning of the entire network.

A limit for acceptable axial shear strength has been proposed in this work corresponding to 0.040 MPa, which can be used in an initial assessment. A specific requirement for the current conditions can be determined based on the pipe's dimension, laying depth and friction between the casing and the filling material. The requirement is based on how much shear stress an external load on the pipeline can cause. For RISE plug method, the requirement for the shear strength of the plug becomes about three times greater based on the correlation between plug method and axial method.

It turned out that in the normal case 6-7 plug samples are required to determine an average value of the shear strength with acceptable measurement uncertainty. To assess the results of the shear strength, absolute values for each pipeline can be compared with associated requirements. To assess degradation, the ratio between the shear strength of the supply and return lines can be calculated.

In the chemical analysis, polyurethane has been examined by infrared spectroscopy (FTIR) to determine an absorption index for two bonds C=O and N-H in the urethane group at the wavenumbers 1712 cm^{-1} and 1512 cm^{-1}, respectively. These bonds are affected by thermal and oxidative degradation. An absorption index is calculated by normalizing the intensity of absorption peaks from these bonds with the peak intensity at the wave number 1595 cm^{-1} resulting from the bonds in the aromatic rings, which are very thermally stable. An absorption ratio has been formed by analysing insulation closest to the service pipe and unaffected insulation far from the service pipe. The absorption ratio shows the degradation of the polyurethane insulation of the supply and return line separately. The absorption relationship of absorption ratios between supply and return lines quantifies the degradation of the supply line relative to the return line.

The shear strength and IR absorption relations should be consistent. Both conditions should be less than 1 or about 1, as the supply line should degrade faster with time than the return line which is exposed to significantly lower temperature. Furthermore, the IR absorption ratio for the return line should normally show that no degradation has taken place, as the temperatures are low in the return lines.

The district heating pipelines analysed in the project generally had, with a few exceptions, a sufficiently good status for continued operation. Most of the pipelines were also not considered to have been exposed to a high operating temperature for many years. Two of the pipelines had a service time of just under and above 30 years, respectively, at the reference temperature of 95 ° C. The other eight had significantly shorter service times at the same temperature.

Two workshops have been conducted. A reasonable temperature level for accelerated ageing tests has been agreed with the participants. A platform for international continued collaboration has been created together with others within the IEA DHC for continued research on methodology for lifetime prediction of pre-insulated district heating pipelines. Work on this theme will also continue in 2022 in a twin project "Resource efficient District heating and cooling networks - new materials, status assessment and lifetime prediction".

10 Suggestions for future work

The work with life expectancy assessment of pre-insulated district heating pipelines has entered an exciting phase in view of the energy crisis in Europe and the global sustainability aspect. We at RISE have worked multidisciplinary in national and international collaboration. To be able to both define and solve challenges regarding pre-insulated district heating pipes, work spans over mechanics, chemical and polymer technology. When it comes to maintenance planning based on life expectancy assessment, the work is not finished, but we have the direction ready for us.

Research for a refined methodology for service life prediction of pre-insulated district heating pipes should continue in both national and international collaboration via the platform created within IEA DHC. A project description for a future project is being formulated and the project is intended to be a so-called "Task shared project". A parallel Swedish project is also planned.

Better / new calculation models are needed to be able to make more reliable lifetime predictions. The models need to be based on relevant experiments, which accelerate but do not change the behaviour of the degradation processes. All environmental factors that affect the degradation processes must be considered such as cyclic mechanical loads.

Further testing of naturally aged district heating pipes in the field would also provide valuable information for assessments of the remaining service life of pre-insulated district heating pipes. Ageing tests for quality assurance and methodology for assessing the remaining service life of district heating pipes in the current standard, need to be reviewed, discussed internationally, and improved by consensus.

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Keywords

Lifetime prediction, status assessment, accelerated ageing, district heating pipes, field method for testing, shear strength, chemical analysis, FTIR, thermo-oxidative degradation

LIFETIME PREDICTIONS AND STATUS ASSESSMENTS OF DISTRICT HEATING PIPELINES

The project has focused on district heating pipes built up of steel service pipes, polyurethane insulation (PUR) and polyethylene casing. The project had two main objectives: A field method should be developed to measure the status of district heating pipelines regarding shear strength and an internationally accepted methodology for service life prediction with respect to lost adhesion would be presented.

A field method (RISE plug method) to assess the status of district heating pipelines in operation has been developed in the project. The method measures the adhesive strength (shear strength) between the insulation and the service pipe. The field method has been supplemented with a chemical analysis of removed insulation in the laboratory. A method to compare service time at a selected reference temperature for different district heating pipelines has been presented.

About methodology for service life prediction, the research situation has been determined through a literature review. A platform for international continued collaboration has been created together with others within the IEA DHC for continued research on methodology for lifetime prediction of pre-insulated district heating pipelines.