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Preface

The project ”Long term effects of repetitive axial loads on district heating pipes and their importance for service life” has been financed by Swedish Energy Agency (as a projects included in the Termo program) and Energiforsk as well as the project partners who are Öresundskraft AB, Jönköping Energi AB, Vattenfall AB, Göteborg Energi AB, E.ON Energiinfrastruktur AB, Kraftringen Energi AB, Powerpipe Systems AB, Cederkrantz Gård & Konsult i Väst AB with the support of Thermtest Europe AB, FV Konsult i Väst HB and RISE. The outcome of this project is based on contributions of all partners' work in collaboration with a reference group from Energiforsk and the FutureHeat program.

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Sammanfattning

Ett energieffektivt och hållbart fjärrvärmesystem (FV-system) med lång livslängd kan i hög grad bidra till effektivare användning av råvaror, minskad energiförbrukning, bättre ekonomi och samtidigt begränsa negativ miljöpåverkan. Förutsättningen för detta är att ha korrekt kunskap om vilka faktorer som påverkar och begränsar livslängden för FV-system. FV-system som används idag, ofta kallade tredje generationens system, består av ett hölje av högdensitetspolyeten (HDPE), ett isolerande lager av styvt polyuretanskum (PUR) och ett stålmedierör för transport av värmebäraren.

För att säkerställa både rörens mekaniska och termiska prestanda krävs god vidhäftning mellan komponenterna. Under normala driftsförhållanden utsätts PUR som är i kontakt med stålröret för hög temperatur, vilket i kombination med syre orsakar nedbrytning. Nedbrytningen sker gradvis under drifttiden och är svår att upptäcka innan ett haveri inträffar. Den allmänna trenden idag är en gradvis övergång till lågtemperatur FV-system. Dessa system utnyttjar flera olika energikällor vilket innebär större temperaturfluktuationer.

Tidigare studier har visat att medan lägre temperaturer minskar nedbrytningshastigheten, skapar större temperaturfluktuationer axiella skjuvkrafter som har en motsatt effekt. Syftet med detta projekt var därför att skaffa kunskap om hur man utformar test- och beräkningsmetoder som behövs för att skapa tillförlitliga livslängdsprognoser för FV-ledningar. Detta med hänsyn tagen till de kombinerade effekterna av lägre temperaturer och skjuvkrafter som induceras genom fluktuerande temperaturer.

I denna studie utsattes rör tillverkade i ordinarie produktion med både kontinuerlig (Conti.) och diskontinuerlig (Disconti.) metod för långtidsåldring vid 140 °C och två olika nivåer av repetitiva mekaniska belastningar samt två olika långa cykelperioder. Som jämförelse utfördes även åldring vid samma temperatur utan mekanisk belastning och därutöver exponering för repetitiva mekaniska belastningar vid rumstemperatur.

Mätningar av vidhäftningsstyrkan visade ingen minskning efter den totala åldringstiden upp till 18 000 timmar, förutom för ett Disconti.-rör som var exponerat för den högsta mekaniska lasten och den långa cykeltiden. Detta rör visade ett första tecken på försämring först efter 16 000 timmar. FTIR-analys visade sig vara en betydligt känsligare metod för att upptäcka tidiga tecken på nedbrytning.

För Disconti.-rör som exponerats för den kombinerade effekten av mekanisk belastning och hög temperatur, är de första tecknen på nedbrytning synliga hos det rör som exponerats för den högsta lasten och den långa cykeln vilket inträffar efter cirka 6 000 timmar. Hos det rör som exponerats för den högsta lasten och den korta cykeln detekterades nedbrytning efter cirka 8 000 timmar. Slutligen visar det rör som exponerats för den lägsta lasten och den korta cykeln tecken på nedbrytning efter cirka 10 000 timmar. Nedbrytning indikeras med FTIR-analys genom reduktion av topp-intensiteten vid 1712 och 1512 cm^{-1}. För rör som endast exponerats för hög temperatur blev det första tecknet synligt efter 15 000 timmar vid 1712 cm^{-1}.

Det första tecknet på nedbrytning för Conti-röret som exponerats för både hög temperatur och mekanisk belastning uppträder efter 14 000 timmar och syns endast som en minskning av toppintensiteten vid 1712 cm^{-1}. Det är också intressant att notera att röret med gasbarriär som exponerats för samma åldringsbetingelser inte visar några tecken på nedbrytning ens efter 18 000 timmar.

För att säkerställa validiteten med de experimentella resultaten testades flera rör i fält där ett och samma rör testades på två olika platser, nämligen i glidzonen, där den axiella mekaniska skjuvbelastningen antas vara störst, och i fix-zonen, där den mekaniska belastningen antas vara liten/försumbar. Slutsatsen från fältmätningarna är att dessa resultat bekräftar överensstämmelsen med laboratoriestudierna, nämligen att nedbrytningen är större i glidzonen än i fixzonen med en sannolikhet på 97,5 % baserat på IR-mätningar.

Slutligen utfördes en serie mätningar av värmeledningsförmågan på samma FV-rör som exponerades för olika åldringsmetoder. Den viktigaste slutsatsen från dessa tester är att metoden visar stabila och sammanhängande resultat. Alla prover visar en långsam ökning av värmeledningsförmågan över tid i intervallet 3 till 6 % för alla rör. Det är dock viktigt att påpeka att accelerationsfaktorn för gasutbytet, som är den huvudsakliga processen bakom förändringar i värmeledningsförmågan, var endast 2 i våra experiment, vilket betyder att den totala åldringstiden i laboratorieexperiment motsvarar högst 4 års faktisk användning.

Resultat från denna undersökning visar att axiella skjuvspänningar i FV-ledningar har en betydande inverkan på livslängden. Detta innebär att rör i glidzonerna är mest utsatta för nedbrytning och bör undersökas först. En annan konsekvens är att metoder för accelererad åldring och livslängdsuppskattning bör revideras i enlighet därmed. FTIR-analys är en betydligt känsligare metod för att upptäcka tidiga tecken på nedbrytning av PUR närmast stålröret jämfört med mätning av vidhäftningsstyrkan. Metoden kan därför ses som en kompletterande metod till mätning av vidhäftningsstyrkan.

Vi tror att resultaten från denna studie kommer att ha en betydande inverkan på framtida tillgångsförvaltning hos nätoperatörer samt optimering och ökad hållbarhet i systemen. Våra resultat spreds under projektets gång på olika sätt till den svenska FV-industrin och även internationellt för maximal uppmärksamhet och effekt. En ny metod PipeOpsy^{TM} (RISE method SP5790) har använts för provning, utvärdering och statusbedömning av förisolerade FV-rör både i den experimentella delen och i fält samt i samband med det internationella arbetet i det här projektet. De alltigenom positiva erfarenheterna från användningen av metoden har bidragit till att metoden finns numera tillgänglig för kommersiell användning av FV-sektor.

Summary

Increased energy performance and longer service life of district heating (DH) systems can greatly contribute to more efficient use of raw materials, reduced energy consumption better economy and at the same time limited environmental pollution. The prerequisite for that is to have correct knowledge of what factors influence and limit the service life of DH systems. DH systems currently in use, often referred to as third-generation systems, consist of a casing pipe made of high-density polyethylene (HDPE), an insulating layer of rigid polyurethane foam (PUR) and a steel service pipe for transporting the heat carrier.

To ensure both the mechanical and thermal performance of the pipes, good adhesion between the components is required. Under normal operating conditions, PUR that is in contact with the steel pipe is exposed to high temperature and oxygen that cause degradation which occurs gradually during the service time and is difficult to discover before a failure happens. The general trend today is a gradual transition to low-temperature DH systems but at the same time larger temperature fluctuations.

Previous studies have shown that while lower temperatures reduce the rate of degradation, larger temperature fluctuations create axial shear forces that have the opposite effect. The aim of this project was therefore to gain knowledge about how to design methods needed to obtain reliable lifetime prediction for DH pipes, when considering the combined effects of lower temperatures and induced shear forces by fluctuating temperatures.

In this study, pipes from regular production using both continuous (Conti.) and discontinuous (Disconti.) methods were subjected to long-term ageing at 140 °C with two different, repetitive mechanical loads and two cycle periods. For comparison, ageing was also performed at the same temperature but without mechanical load and in addition an exposure to load at room temperature.

Measurements of adhesion strength showed no reduction after the total ageing period up to 18.000 h except for one Disconti. pipe exposed to the highest mechanical stress and long cycle period which showed a first sign of decline first after 16.000 h. FTIR analysis proved to be a significantly more sensitive method for detecting early signs of degradation.

For Disconti. pipes exposed to the combined effect of mechanical load and high temperature, the first signs of degradation are visible after about 6.000 h for the pipe exposed to the highest stress and long cycle followed by the pipe exposed to the highest stress and short cycle after about 8.000 h and finally the pipe exposed to the lowest stress and short cycle after about 10.000 h. Degradation was indicated by FTIR analysis as reduction in peak intensities at 1712 and 1512 cm^{-1}. For the pipe exposed to high temperature only, the first sign becomes visible after 15.000 h at 1712 cm^{-1} only.

The first sign of degradation for the Conti. pipe exposed to both high temperature and mechanical stress appears after 14.000 h and is only visible as reduction of 1712 cm^{-1} peak intensity. It is interesting also to note that the pipe with gas barrier exposed to the same treatment show no signs of degradation even after 18.000 h.

To find conformity with the experimental results, several pipes were tested in the field at two different locations on the same pipe namely in the sliding zone, where axial mechanical shear load is assumed to be the greatest, and in the fixed zone, where mechanical shear load is assumed to be small/negligible. The conclusion from the field measurements is that these results confirm the agreement with the laboratory studies namely that the degradation is

greater in the sliding zone than in the fixed zone with a probability of 97,5 % based on IR measurements.

Finally, a series of thermal conductivity measurements were performed on the DH pipes exposed to various laboratory ageing conditions. The main conclusion from these tests is that the method shows stable and coherent results. All samples show a slow increase in the thermal conductivity over time in the range of 3 to 6 % for all samples. However, the acceleration factor of the gas exchange that is the main process behind changes in thermal conductivity was only 2 in our experiments which means no more than 4 years of actual use.

Results from this investigation show that axial shear stresses in DH pipes have a significant impact on service life. This means that pipes in the sliding zones are most susceptible to degradation and should be investigated first. Another consequence is that methods for accelerated ageing and lifespan estimation should be revised accordingly. FTIR analysis is a significantly more sensitive method for detecting early signs of PUR degradation closest to the steel pipe compared to measurement of adhesion strength. The method can therefore be seen as a complementary method to measuring adhesion strength.

We belief that the results of this study will have a significant impact on the future asset management by network operating companies and optimization and increasing sustainability of the systems. Our results were disseminated in different ways to Swedish DH industry and internationally for maximum attention and impact. A new method named PipeOpsy^{TM} (RISE method SP5790) has been used for testing, evaluation and status assessment of pre-insulated DH pipes both in the experimental part and in the field as well as in connection with the international work in this project. The consistently positive experiences from the use of the method have contributed to the method now being available for commercial use in the DH sector.

Abbreviation list

Af- acceleration factor

AGFW- Energy Efficiency Association for heating and cooling and combined heat and power

ATR- Attenuated Total Reflectance

Conti.- Continuous manufacturing method

Disconti.- Discontinuous manufacturing method

DH- district heating

DHP- District heating pipe

EVOH- ethylene vinyl alcohol

FTIR- Fourier Transform Infra-Red

FV- Fjärrvärme

HCU- Hafen City University Hamburg

HDPE- High-Density Polyethylene

PUR- Polyurethane

WP- work package

1 Introduction

District heating (DH) is an essential public energy service that delivers heat from one or more sources to a plurality of consumers. Just heating and cooling are estimated to account for around half of the end-user energy worldwide and 40 % of its energy-related global carbon dioxide (CO_2) emissions. In 2022, DH production remained relatively similar to the previous year and was accounted for around 9 % of the global final heating needs in buildings and industry. Several DH markets have seen increasing dynamism recently, particularly in Europe, where DH has gained greater policy support since 2022 as a result of energy security concerns arising from the energy crisis[1].

Increased energy performance and longer service life of DH pipe systems can greatly contribute to more efficient use of raw materials, reduced energy consumption and at the same time reduced environmental pollution. The prerequisite for improving the use and evaluation of DH pips is to have correct knowledge of the influencing factors. This is both a challenge and an opportunity. Today's DH pipes have been developed for high-temperature operation, originally based on fossil primary energy sources.

Current pipe systems are often referred to as third generation systems which consist of a casing made of high-density polyethylene (HDPE), an insulating layer of rigid polyurethane foam (PUR) and a steel service pipe for transporting the heat carrier. The heat carrier in most cases is water. This pipe construction requires good adhesion between the components to function well. The most sensitive part of the construction is adequate adhesion between the PUR insulation and the steel pipe. The insulating material is in direct contact with the hot service pipe resulting in gradual degradation of the PUR material at the interface.

As the PUR deteriorates, its adhesion to the service pipe is reduced and finally concludes in detachment of the foam from the steel pipe. When detachment occurs the steel pipe can move freely increasing mechanical stresses at bends and other fittings in the pipeline system. These movements are caused by thermal expansion and contraction of the steel pipe as the operating temperature varies. The loss of adhesion between PUR foam and the service pipe can result in serious damage to the network, interrupted heat delivery and costly unexpected repairs.

Another key factor for efficient DH use is that the thermal conductivity of the PUR foam remains low throughout a DH pipe service life. If the thermal conductivity increases above stipulated limits, thermal losses increase and energy efficiency decreases. This can have a large monetary impact as heat is lost in transit and does not reach the end-user. The insulating properties of the PUR can be impacted by many factors, amongst them are gas exchange, mechanical damage, water damage, and damage from a too hot service pipe. Methods for testing the thermal properties of pipes that may have been exposed to any of the above conditions would therefore be valuable, especially if the testing can be done when pipes are still connected as integrated parts of a larger DH system.

The total replacement value of DH networks in Sweden alone is estimated to be more than SEK 100 billion (Euro 9 billion). Consequently, there is a strong economic and environmental incentive in continuing to use the existing DH networks for as long as possible. This means that any new operating conditions in the future must be considered. As societal norms shift towards tackling and coping with anthropogenic climate change, the availability of high-temperature heat supply from fossil fuels is declining. A gradual transition to low-temperature DH systems which makes it possible to integrate energy from renewable sources and waste heat simultaneously is therefore both required and expected.

Aligning with the Net Zero Emissions by 2050 (NZE) scenario requires significantly stronger efforts to rapidly improve the energy efficiency of existing networks and switch them to renewable heat sources[2]. Prefabricated DH pipes were initially designed for at least 30 years of service life with an operating temperature of 120 °C, according to the standard EN 253[3]. The question we must now answer is how long new and current DH pipelines can operate when future operating conditions with lower operating temperatures but with greater temperature fluctuations are considered.

Previous studies have shown that while lower temperatures reduce the rate of degradation, larger temperature fluctuations create axial shear forces that have the opposite effect. Consequently, the overall aim of this project was to improve and find technologies and methods needed to obtain reliable lifetime prediction for DH pipes, when considering the combined effects of lower temperatures and induced shear forces by fluctuating temperatures. The results of this study are expected to have a significant impact on asset management for network operating companies and optimization and increasing sustainability of the systems. The results may also provide guidance for general urban planning. For maximum attention and impact, an important goal of the project was also to disseminate results to Swedish DH industry and beyond through national and international cooperation.

2 Background / state of knowledge

The experimental part of the study has been carried out on prefabricated DH pipes which have been the dominant type during the last 40 years. These pipes consist of a HDPE casing, PUR insulation and steel service pipe. All the pipes used in the study were manufactured using the ordinary production methods.

For comparison, similar pipes containing a gas barrier in addition were also studied in the same way. The DH pipes degrade over time at a rate that depends on the operating conditions and the quality of the pipes. A basic knowledge of the relationship between temperature, different stress levels and the rate of degradation was extracted here from a series of laboratory experiments executed under well-controlled conditions. In the parallel project entitled “Effects of mechanical loads on ageing of district heating pipes” old, naturally aged DH pipes were examined to find conformity with the experimental results.

2.1 Third generation DH pipes

To date, four generations of DH pipes have been established. The first generation was based on distribution of steam in metal pipes insulated with mineral wool or another insulating material and placed inside concrete ducts. The second generation had the same design but with hot water as a heat carrier instead of steam in the service pipes. The third generation which is also the current generation has another design than the first two generations. It consists of a steel pipe with hot water as a heat carrier, insulated with rigid PUR foam and protected by a casing of HDPE. This type of pipes is normally directly buried underground.

The current and most dominated third generation called also prefabricated DH pipes were developed and manufactured since the 60s and has been investigated in this project. These pipes have many advantages compared to the design of the first and second generation of pipes because all the components are bonded together and act as a composite structure with the purpose, to distribute hot water with as little heat loss as possible.

The most sensitive part of the prefabricated DH pipes is the PUR insulation which is in contact or close to the hot service pipe and thus exposed to degradation which affects DH pipes service life. Rigid PUR is a polymeric material that has a limitation with respect to exposure to high temperatures, oxygen and moisture which causes chemical degradation leading to loss of adhesion to the steel pipe. Under normal operating conditions, PUR is protected from water but is exposed to high temperature and oxygen that cause degradation which occurs gradually during the service time and is difficult to discover before a failure happens.

It shall be noted that the chemistry of PUR has a variation from time to time and between different manufactures. Such variations may have a minor impact on the physical characteristics. Pipes in the referred tests below contain the same and nowadays generally used blowing agent (C-pentane).

In general, the possible degradation mechanisms in PUR insulation are:

- Thermal degradation: At high temperatures (≥150 °C), PUR degrades through chain scission (depolymerization).
- Thermo-oxidative degradation: Oxygen diffuses through the HDPE casing and causes degradation of PUR through oxidation at a rate that increases exponentially with increasing temperature.

- Mechano-chemical degradation: Mechanical stress during thermo-oxidative degradation often accelerates the degradation process of the polymeric material due to morphological changes in the material caused by stress.
- Gas exchange: Carbon dioxide in the cell structure of PUR diffuses out and is replaced by air diffusing in through the casing. This process leads to increased thermal conductivity and enables thermo-oxidative degradation in the next step due to the presence of oxygen at the interface with the steel pipe.

For many years, thermal ageing at elevated temperatures has been used to study the degradation process and to predict the service life of DH pipes. The lifetime was calculated using an Arrhenius equation, and test results of shear strength obtained after accelerated ageing tests with duration of 3600 h at 160 °C or 1450 h at 170 °C according to EN 253[3].

However, one of our previous investigations revealed that accelerated ageing tests at 150 °C and higher temperatures should not be used for calculation of service life at the service temperature because the results do not follow the Arrhenius relationship[4]. This is because at high temperatures depolymerization reaction is predominant while at temperatures below 150 °C thermo-oxidation is predominant. Thermal depolymerisation of polyurethane insulation at temperatures above 150 °C resulting in formation of isocyanates has been proven, among others, in a study of Akram[5].

The degradation of PUR is complex and leads to several alterations of the chemical structure, but it begins at the thermally weakest linkage within the polymer chain which is the urethane linkage. It was demonstrated in our previous investigation that thermo-oxidative degradation of PUR can be evaluated by studying changes in the intensity of two characteristic peaks corresponding to chemical bonds C=O and N-H in the urethane linkage using FTIR (Fourier Transform Infra-Red) spectroscopy[6].

In addition to high temperature, there is another important factor that must be considered which is mechanical stress. It is generally recognised that application of a mechanical stress to a polymeric material often accelerates degradation of the material, due to morphological changes in the material caused by the stress which affects the degradation mechanisms[7],[8].

In a previous study, DH pipes were investigated after accelerated ageing at 130 and 140 °C with and without the influence of axial shear stresses[9]. The measurements of adhesion strength and FTIR study revealed a significantly higher degradation rate of the PUR foam when the pipes were mechanically stressed during the thermal ageing compared to thermal ageing without stress. The results gave also a strong indication that the effect of combined mechanical and thermal ageing was due to faster chemical degradation of the PUR foam and not due to fatigue.

2.2 Third generation DH-pipes with diffusion barrier

It has been shown in several studies that the most important ageing process in DH pipes is thermo-oxidative degradation of PUR. This process occurs when the gas exchange has taken place by carbon dioxide diffusing out and oxygen diffusing into the PUR. To prevent or delay gas exchange, a gas barrier is sometimes used in DH pipes for example aluminium foil or a thin layer of ethylene vinyl alcohol (EVOH). The foil or layer is located between the casing and the insulation of PUR foam to prevent diffusion of air.

In addition to slowing down the rate of degradation it has been shown that there is a 20 % reduction of heat losses for prefabricated pipes with diffusion barrier comparing to traditional ones[10]. In this study, DH pipes with gas barrier were investigated with respect to insulation capacity and degradation rate and compared to DH pipes without a diffusion barrier to obtain a quantitative estimation of the benefit of a gas barrier.

3 General and Specific Goals

The overall goal of this project was to develop new detailed knowledge about how cyclic mechanical loads affect the service life of prefabricated pipes and finally to propose a new method for accelerated ageing test and a new model for calculation of expected service life. The challenges for network owners consist of creating a system for cost- and environment-efficient maintenance and cost-effective operation considering the impact of operating conditions on service life of the pipes. One of the goals was also implementation of more relevant requirements regarding lifetime for new DH pipes in relevant standards.

The outcome of this project is expected to contribute to the following developments:

- increase sustainability of DH pipe systems
- increase competitiveness of Swedish energy sector, its knowledge and services to create business opportunities in Sweden and in other countries
- contribute to the development of DH systems for the future operating conditions
- contribute to expanded basic knowledge ahead of revision of European standards for the DH sector such as EN253

To achieve the overall goal, following sub-goals were defined and linked to the different parts of the project:

- establish relationship between different stress levels, number of cycles, and the rate of degradation at elevated temperatures.
- investigate effect of cyclic mechanical loads only, without the influence of thermo-oxidative degradation through evaluation at room temperature.
- confirm the effects of cyclic mechanical loads on the status of old DH pipes obtained by measurements in the field. Old DH pipes were tested in fix and sliding zones to find out if pipes in sliding zones are more degraded than pipes in the fixed zones.
- investigate effect of diffusion barrier in DH pipes, exposed to accelerated thermal and mechanical ageing.
- develop new knowledge for future revision of the EN- standards

4 Scope and design of the study

The project has been executed in five work packages (WP) including the parallel project “Effects of mechanical loads on ageing of district heating pipes” funded by Energiforsk AB within the framework of the FutureHeat program.

4.1 DH pipes used in the study

DH pipes were manufactured using either the continuous (Conti.) or discontinuous (Disconti.) methods. In the Disconti. method each pipe is manufactured individually. The service pipe is centred in the casing after which the reactive mixture that will form PUR is injected through a hole in the casing in the middle of the pipe or from one of the ends. When the PUR foam is formed and expands, it adheres to the steel pipe and the casing.

The Conti. method involves spraying or casting the insulation around the service pipe, then extruding the casing around the insulation. Finally, the pipes are cut to the desired lengths. Conti pipes, allows for faster and more efficient manufacturing of pipes and can lead to finer and more homogenous foam cell size which gain a foam with more uniform density. It allows also for production of pipes with a diffusion barrier to prevent gas diffusion and maintain insulation performance.

One of the tasks in this study was to investigate how pipes manufactured with different production methods and pipes with a gas barrier are affected by long-term ageing. Short information about pipes included in this study and the exposure conditions they have been exposed to is given in Table 1.

4.2 Implementation

The work has been divided into different work packages (WP) in a planned and coordinated manner. The work in WP1 and WP2 included the experimental study at RISE laboratory. The result from the experimental investigations represents the physical behaviour of the pipes and gives better information than simulations, as boundary conditions can be captured much more realistically when real conditions are mimic. Experimental investigations help to gain new knowledge without compromising the systems negatively. In WP3 measurements were performed in the field during operation on the existing pipes in different networks to find confirmation of the experimental results. WP4 included international collaboration and discussions in the field of DH pipes testing with researchers, pipe suppliers and energy companies to gain a broader view of the topic.

WP5 managed coordination and dissemination as well as creating and support transparency, allowing the project work to assess progress. Reporting development of a quality and risk management plan as well as economic status to the project partner and financier. Risk management included regular exchange of information on progress to recognize deviations from the work plan and the updating of a risk repository. Organization of meetings to facilitate frequent exchange and discussions of synergies between WPs, tasks, and results was another part in this WP. In the following part, work packages included in this study are briefly described:

WP1: Effect of cyclic mechanical loads on the degradation rate

The thermo-mechanical stress on pipes during operation time depends on the size and number of temperature fluctuation. In a previous study[9], it was clearly shown that the thermo-oxidative degradation of PUR at high temperatures was significantly accelerated when repetitive mechanical loads were applied simultaneously on the pipes investigated in that study. The purpose of WP1 was therefore to find out how different loads and number of load cycles affect the degradation rate of pipes manufactured by Disconti. and Conti. methods. Different types of pipes were aged at high temperature without mechanical load and with different mechanical loads (for details see Table 1). After different ageing periods, pipes were examined for adhesion strength and chemical degradation of the part of PUR foam that was in contact with the service pipe. In addition, thermal conductivity of PUR was measured as well.

The effects of cyclic mechanical loads on degradation degree of PUR were examined partly at a constant high temperature of the steel pipe and partly at room temperature. For high temperature ageing, 140 °C was used, which is the highest permissible temperature for maximum acceleration of degradation processes in the rigid PUR foam.

At low temperatures no thermo-oxidative degradation is expected to occur within a foreseeable time. Long term tests at room temperature using the same set of cyclic mechanical loads as in the high temperature ageing tests were performed to find out whether the mechanical loads themselves can cause any deterioration of the adhesion, for example due to fatigue or degradation.

WP 2 – Long term effects of diffusion barrier in DH pipes

It has been shown in several studies that the most decisive ageing process in DH pipes is thermo-oxidative degradation of PUR foam[5,9,10]. This process occurs when the gas exchange takes place by carbon dioxide diffusing out and air diffusing into the PUR foam and thermo-oxidation process start close to the hot service pipe. To prevent gas exchange, a thin foil (aluminium or plastic) is used as diffusion barrier against oxygen. The foil must be located between the casing pipe and the insulation of PUR foam. In addition to slowing down the rate of degradation, it has been shown that there is a 20 % reduction of heat losses in pipes with diffusion barrier comparing to traditional ones[11].

In WP 2 the work was focused on evaluating the long-term effects of the gas barrier by comparing the results from pipes without and with the gas diffusion barrier after thermal ageing with and without mechanical loads. In addition to evaluating the adhesion strength and chemical degradation of PUR, the thermal insulation capacity was also studied because the gas barrier is expected to hinder gas exchange and thus to prevent worsen the insulation capacity.

Table 1: Compilation of all pipes that have been included in the study and the exposure conditions they have been exposed to.

Temperature [°C]	Load [kN]	Cycle time [min]	Barrier	Load	Pipe	Note
140	8	60	No	Yes	P1C	Disconti
140	25	60	No	Yes	P2A	Disconti
140	25	30	No	Yes	P2C	Disconti
23	25	30	No	Yes	P1A	Disconti
30-140	Water cooling	60	No	No	P3A	Disconti
140	0	-	No	No	P1D	Disconti
23	0	-	No	No	P2D	Disconti Ref. pipe
140	25	30	Yes	Yes	LD2	Conti
140	25	30	No	Yes	L1	Conti
23	0	-	Yes	No	LD1, 3, 4	Conti Ref. pipe
23	0	-	No	No	L3, 4	Conti Ref. pipe
140	0	-	No	No	L2	Conti

WP 3 – Effects of mechanical loads on the status of DH pipes in operation - comparison between sliding and fixed zones

WP3 consisted of a separate project entitled “Effects of mechanical loads on ageing of prefabricated district heating pipes” funded by Energiforsk AB within the framework of the FutureHeat program. However, this investigation was also an integral part of the current project.

Under normal operating conditions, DH pipes are exposed to significant temperature variations due to variations in weather conditions and customer demands. When interacting with the ground, the temperature variations create changing mechanical loads on the pipes in sliding zones. Previous laboratory studies showed that mechanical stress accelerates the degradation of PUR at high temperatures. To find conformity with the experimental results, testing of supply pipes in the field was performed at various locations, in and outside the pipes’ sliding zones, using RISE PipeOpsy^{TM} method[12].

WP 4 – International collaboration

One part of the project has also included the exchange of experiences and knowledge with international experts in the field concerning methodology for accelerated ageing and lifetime prediction of DH pipes. The final goal is to develop an internationally accepted methodology for accelerated ageing and lifetime prediction of DH pipes. The collaboration has involved experts from DH industry, standardisation committee and academia and was achieved through workshops and meetings on an international level both virtual and face-to-face.

An important part of international collaboration was participation in the international IEA-DHC projects Task Share 6 and Task Share 8. Task Share 6 with the title “Status assessment, ageing, lifetime prediction and asset management of District Heating pipes” was directly connected to the goals of this project. RISE has played a major role in this Task Share, by among other things, leading two subtasks viz. Subtask B - Ageing of DH-pipes and Subtask C – Lifetime prediction of DH-pipes and co-leading two other subtasks viz. Subtask A – status assessment of DH pipes and Subtask E – future perspective. TS6 project is coordinated by AGFW in Germany. Task Share 8 with title “Experimental investigations of DHC systems” has a wider scope than TS6 and is connected to RISE DH testbed and experimental designs related to research in DH system. TS8 project is coordinated by Fraunhofer institute in Germany.

By international collaboration in this project and other international projects, we have created better conditions for cooperation between Swedish companies and other countries industry e.g. German, Swiss, Dutch and Italian DH networks and for using Swedish technology. The knowledge of this project has been presented at conferences and a workshop requested by the European standardization group TC107.

WP 5 – Project management

This work package has handled project management, administration, communication and dissemination of results. It was important to ensure an efficient time and quality management of the project through administrative and scientific project coordination. The objectives were also to coordinate, structure and oversee collaboration between partners as well as implementation of activities, completion of milestones and timely production of deliverables. The project progress and economical status have been reported to Swedish Energy Agency according to the agreement and time schedule. The project time was prolonged once from 2024-12-31 to 2025-09-12.

At the start of the project, a reference group was formed consisting of experts from Energy companies and Energiforsk. A project team consisting of RISE, consultants involved in the project and DH companies has also been formed. The consultants were Cederkrantz Gård & Konsult and FV Konsult i Väst. The participating DH companies were: Öresundskraft, Jönköping Energi, E.ON Energiinfrastruktur, Kraftringen Energi, Göteborg Energi, Powerpipe Systems and Vattenfall. During the project period, 9 project meetings with the reference group, 4 extra meetings with pipe manufactures, monthly meetings with executive group have been held to exchange information on progress and possible deviations from the work plan, discuss the results and plan continued work. Status and economical reporting to Swedish Energy Agency have been done annually.

The second important part of this work package was the dissemination of results from the project. The results were disseminated through national and international workshops and conferences. Additionally, some papers have been published, see publication list in chapter 12. The achievements of this study have been presented in the following forums:

- Oral presentation at Ecotec Conference- International Conference on establishment of cooperation between companies- Linnaeus University in Kalmar- November 2022

- Oral presentation at workshop with Standardisation committee TC 107 WG 10 and TC 107 WG3- Stockholm- April 2023
- Conference paper to the 18th International Symposium on District heating and cooling, September 2023 Beijing China via IEA- DHC Annex TS 6
- Conference paper to 9th International Conference on Smart Energy Systems, September 2023 Aalborg Denmark via IEA- DHC Annex TS 8
- Oral presentation at workshop for Annex TS 6, May 2024 Dresden, Germany
- Oral presentation at workshop for IEA- DHC Annex TS 8, November 2024 Roskilde, Denmark
- Poster presentation and contribution to Book of Abstracts at MoDeSt 2024 11th Conference of the Modification, Degradation, Stabilization of Polymers Society, September 2024 Palermo, Italy
- Oral presentation at Swedenergy's Distribution Days - District heating (Distributionsdagarna Fjärrvärme) in January 2025 in Västerås, Sweden.
- Oral presentation at workshop for Annex TS 6, April 2025 Brescia, Italy
- Oral presentation at 19th International Symposium on District Heating and Cooling – for Annex TS 6 session, September 2025 Genk Belgium
- Oral presentation at the 43rd edition of the EuroHeat & Power Congress June 2025, Prague, Czech Republic

5 Experimental

Two types of experimental work were carried out, viz. accelerated aging with evaluation of its effects at RISE laboratory and tests in the field at different locations in Sweden. Fieldwork was carried out with great help from participating Energy companies: Göteborg Energi AB, Öresundskraft AB, Vattenfall AB, E.ON Energiinfrastruktur AB, Jönköping Energi AB, Kraftringen Energi AB.

5.1 Laboratory set up

To perform the experimental part and to simulate the natural ageing processes new experimental equipment was designed and assembled. The pipes used in this study were manufactured both with continuous and discontinuous manufacturing methods. Three twelve meters long Disconti. pipes were manufactured. These pipes were divided into 3,2-meter long parts. The parts from the first 12-meter pipe are designated P1A, P1C and P1D. Pipes P2A, P2C and P2D were cut from the second 12-meter pipe and pipe 3A from the third 12-meter pipe. Pipes designated L1, L2, L3 and L4 are Conti. pipes. Conti. pipes LD1, LD2, LD3 and LD4 were manufacture with diffusion barriers. The ends of the pipes were sealed using HDPE socks and a thick Al-foil to avoid any diffusion of air from the ends of the pipes. To minimize the convection of heat, the steel pipe ends were insulated with mineral wool.

Electrical heating of steel pipes was used for accelerated thermal ageing of the DH pipes. Six electro-mechanical aggregates were used for applying axial forces to the steel pipes creating axial shear stresses for mimicking the natural thermo-mechanical ageing process.

In the experiments, DH pipes of size DN50/160 mm were used. The casing of a DH pipe was fixed, while a repetitive axial force was applied on the steel service pipe. The maximum applied axial force is based on the mechanics of a buried DH pipe, see, *e.g.*, EN 13941. In the soil, the vertical pressure σ_v [Pa] at the DH pipe can be expressed as

$$\sigma_v = \left(H_{co} + \frac{D_c}{2}\right)\gamma \tag{1}$$

Here, the cover above the casing is denoted H_{co}, the casing diameter D_c and the weight density of the soil γ [N/m^3]. The friction force F_f [N/m] per unit length can be calculated as

$$F_f = \pi\, D_c\, \mu\, \sigma_v \frac{1 + K_o}{2} \tag{2}$$

Here, the friction coefficient between the casing and the soil is denoted μ, and K_o is the coefficient of the horizontal soil pressure. The shear stress between the insulation and the service pipe can be calculated using the friction force F_f and the diameter D_{sp} of the service pipe

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

Input data for the calculations of the applied force and corresponding shear stress are given in Table 2. In Table 3, the results of the calculations are given. In a previous investigation[8], the applied force corresponded to a shear stress of 0,031 MPa. In the present investigation, the shear stress has been increased in many experiments with 50 % and in one experiment the force has been decreased with 50 %. The corresponding covers are also given in Table 3.

Table 2: Input data for buried pipe and length of pipes in experiments

Explanation	Notation	Value
Friction coefficient	μ	0,6
Soil pressure coefficient	K_o	0,5
Weight density of soil	γ [kN/m^3]	20
Diameter of service pipe	D_{sp} [mm]	60,3
Diameter of casing	D_c [mm]	160
Length of pipe insulation	L_{exp} [m]	2,8

Table 3: Results of calculation for different cover above DH pipe

H [m]	σ_v [kN/m^2]	F_f [kN/m]	τ_{sp} [MPa]	F_{exp} [kN]
1.2	25.6	5.8	0.031	16,2
1.9	39.6	9.0	0.047	25,1
0.55	12.6	2.9	0.015	8,0

Additionally, for mimicking a similar thermo-mechanical process, a varying temperature between 30-140 °C was applied. The different thermal expansion of the PUR foam and the steel pipe will cause normal stresses close to the steel pipe of the same order as the shear stress caused by friction between soil and casing. The width of the normal stress close to the steel service pipe becomes

$$\sigma_{pur} = E_{pur}\left(\alpha_{pur} - \alpha_s\right) T_{sp} \tag{4}$$

Here, Young's modulus of PUR foam is E_{pur} and the thermal expansion coefficients for rigid PUR foam and steel are α_{pur} and α_s, respectively. The width of the temperature variation is T_{sp} = 110 °C. Assuming that $E_{pur} = 8$ MPa, $\alpha_{pur} = 5 \cdot 10^{-5}$ K^{-1} and $\alpha_s = 12 \cdot 10^{-6}$ K^{-1} then the normal stress in the insulation parallel to the pipe becomes 0,033 MPa. The shear stress in the insulation in a direction 45° relative to the pipe direction becomes 0,017 MPa.

The pipes were set up in two places shown in Figure 1. Figure 2 shows a schematic layout for all DH-pipes. Accelerated thermal ageing tests at 140 °C in combination with a cyclic axial force with specific periods were used.

The time periods of the axial loads were linked to the number of cycles that were selected to expose the pipes to during the project. For house connection, the number of full loading cycles during service in 30 years is estimated to be 1000, see EN 13941. The full load cycle corresponds to a temperature width of 110 °C. A fatigue curve is used for estimating service life and damage of the steel service pipes. The fatigue curve is given as number N_i of cycles the steel can endure at a certain stress range S_i

$$N_i = C\, {S_i}^{-m} \tag{5}$$

The exponent $m = 4$ and C is a constant depending on the steel part. The damage of different number n_i of cycles at specific stress ranges S_i can be expressed as

$$\delta_f = \sum_i \frac{n_i}{N_i} = \sum_i \frac{n_i\, {S_i}^m}{C} = \frac{n_0\, {S_0}^m}{C} \tag{6}$$

Here, the stress range of the full load cycle is denoted S_0 and the number of full load cycles for the house connections is $n_0 = 1000$. The stress range is proportional to the temperature range. From Equation (6), we get

$$\sum_i n_i \, T_i{}^m = n_0 \, T_0{}^m \tag{7}$$

As a first estimate, the number of cycles pertaining to half the maximum range is given as

$$n_{exp} = \frac{n_0 \, T_0{}^m}{T_{sel}{}^m} = 1000 \times 2^4 = 16000 \tag{8}$$

During an experimental time of 2 years, this number of cycles can be achieved with 24 cycles per day. In the network the operation temperature varies slowly, a whole spectrum of temperature ranges can be deducted from the time history. In an experimental set up, simplifications as choosing one frequency for a specific sample pipe must be done. The purpose of estimation done here is to get a relevant number of cycles for the experiments. Hence, two cycle times of the axial force are chosen: 1 hour and half an hour.

In the experiments, the axial force is prescribed to pulsate. The force level is raised to its maximum level for 1-2 minutes, then the cylinder applying the force is locked during nearly half the cycle time. Next, the axial force is decreased to zero for 1-2 minutes and left at zero during nearly half the cycle time.

Figure 1: Pictures of set up for ageing of pipes using cycling load and temperature.

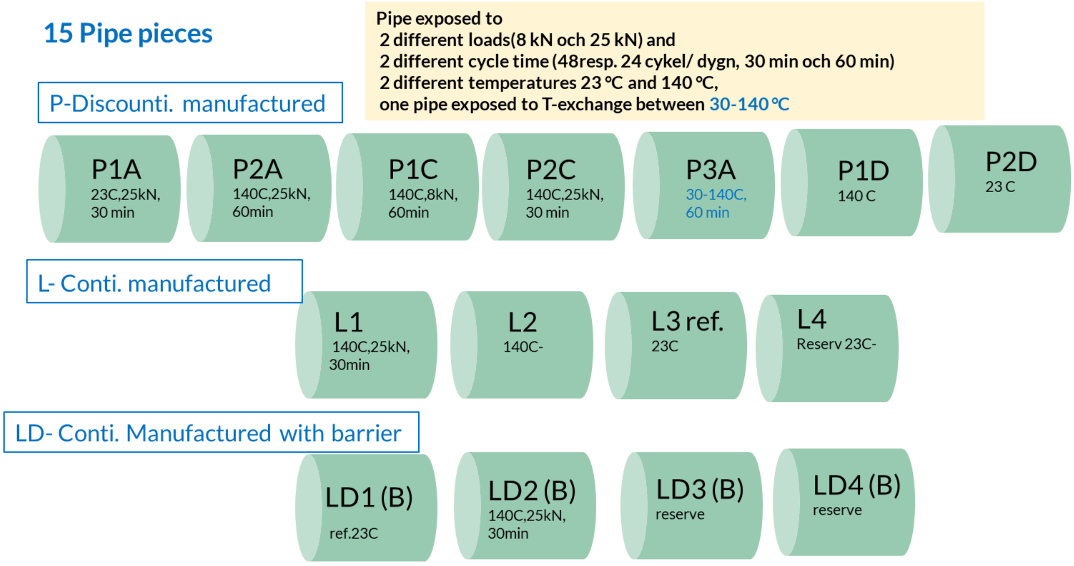

Figure 2: Schematic layout of 15 pipes and their conditions in this project.

5.2 Laboratory ageing experiments

The accelerated ageing tests used in the project were carried out on pipes stored at room temperature (ambient temperature 23 °C), while the steel pipes were connected to an electricity source that delivered enough power to hold 140 °C in the steel pipes during the entire test. An original schematic layout of 15 pipes and their exposure conditions in this project is shown in Figure 2. Some extra pipes have been used after a while when the need arose to replace certain pipes. Pipe L4 has replaced L2 after about half of the project time when the ageing aggregate failed. LD3 has been used as reference in the end of the project for the verification of the reference values from LD1.To estimate how much the degradation processes in PUR in contact with the steel pipe were accelerated in these tests, the following Arrhenius relationship (Equation 9) can be used:

$$t_2/t_1 = \exp[-E_a/R(1/T_1 - 1/T_2)] \qquad (9)$$

where t_2/t_1 is acceleration factor, E_a is activation energy, R is the ideal gas constant 8.314 J/(K mol), T_1 is operation temperature and T_2 is the temperature in accelerated ageing tests. In the current accelerated ageing tests T_2 was 140 °C. If a typical operating temperature is assumed to be 95 °C and the activation energy is assumed to be 103 kJ/mol as was assumed previously[13], the acceleration factor is 41. This means that, for example, one year of accelerated thermal ageing testing is equivalent to 41 years under normal operating temperature. The total ageing time in this project corresponds to about 73 years in operation at 95 °C.

Another property studied in this investigation was changes in thermal conductivity in PUR insulation with ageing time. However, these measurements are not affected by ageing processes caused by the hot steel pipe but are only affected by the gas exchange through the casing. It is well known that when CO_2 gradually diffuses out from the foam and is replaced by air, the thermal conductivity increases in the insulation. The diffusion rate of a gas is directly influenced by the temperature at the casing. An increase in temperature leads to an increase in the kinetic energy of gas molecules. The increase in the diffusion rate of a gas through a gas barrier when the temperature increases from T_1 to T_2 can be quantified as acceleration factor using the similar equation but here E_a is the activation energy for diffusion, T_1 is the temperature of the casing during operation and T_2 is the elevated temperature. E_a for air diffusion through HDPE casing can range from approximately 30 to 60 kJ/mol with specific values depending on the exact gas, temperature, and experimental conditions[14].

A normal temperature in the soil can be assumed to be about 10 °C, while the temperature around the casing pipe was 23 °C in all experiments. If E_a is assumed to be 40 kJ/mol which is a common value for gas diffusion process through HDPE, the acceleration factor is 1,6. If E_a is assumed to be 60 kJ/mol the acceleration factor would be 2. This means that the gas exchange process was maximally accelerated in this study by a factor of 2 which means that two years of study correspond to four years in reality.

5.2.1 High temperature ageing

During operating conditions, DH pipes undergo significant temperature variations due to variations in customer demands, soil-pipe interactions and weather conditions, which cause expansion and contraction of the steel service pipe. This in turn creates an axial shear stress due to the restrain of the pipe by the surrounding soil.

In our previous work, it was demonstrated how the rate of degradation depends on ageing temperature[4] through isothermal ageing tests. It was also shown that the highest ageing temperature that can be used without introducing other degradation mechanisms is 140 °C. The goal of the current project was to investigate how different levels of shear stress and number of load cycles affect the degradation rate. In the current ageing tests, 140 °C was therefore chosen to create maximum degradation rate under different mechanical loading conditions. This was achieved by connecting pipes to electrical cylinders which applied an axial load during a specified period, see Figure 3. Thereafter, the piston was returned to the starting position and no load was applied. In this project, two different load levels and two different cycle times were used, namely 8 kN and 25 kN respective 30 min and 60 min. Pipes designated P1A, P2A, P1c, P2C, L1, LD2 have been exposed to these conditions see Figure 2.

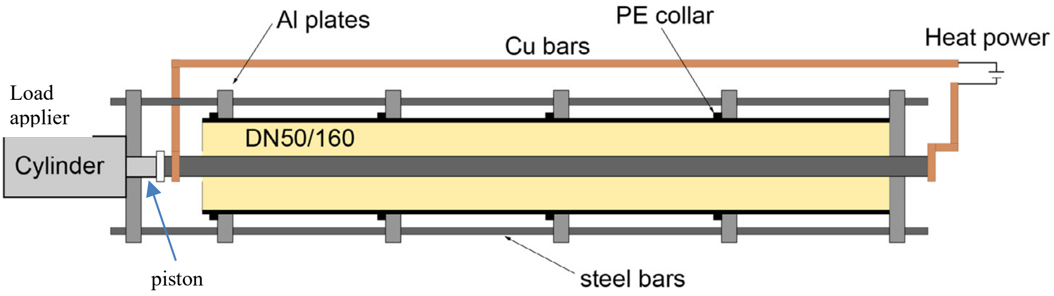

Figure 3: Sketch of the test rig. Steel bars are fixed in the cylinder, and the piston applies force on the service pipe, which is electrically heated

5.2.2 Exposure to cyclic mechanical stress at room temperature

To find out whether the mechanical loads themselves can cause any deterioration of the adhesion, for example due to fatigue, long term experiments were conducted at room temperature because no chemical degradation is expected to happen but applying the same set of load conditions as in high temperature experiments. The pipe P1A in Figure 2 has been used for this experiment.

5.2.3 Long term exposure to cyclic temperature variations

When two materials with different temperature expansion coefficients are bonded to each other - as typical in DH pipes with steel service pipe and PUR insulation, temperature changes introduce tensions at the interface. Because steel pipe is much stronger than the PUR (depends on the Young's modulus) - the tension in the PUR can be calculated from the difference in temperature expansion. The coefficient of thermal expansion for steel varies slightly depending on the specific type of steel and the temperature range, but it is generally around $12 \cdot 10^{-6}$ /K while for rigid polyurethane foam it typically ranges $50\text{-}80 \cdot 10^{-6}$ /K[15]. With this as a starting point, a specially designed experiment was conducted in which axial stress was not created by electrical cylinder but by holding the outer casing and only varying the temperature of the steel pipe between 30 and 140 °C. The pipe P3A in Figure 2 has been used for this study.

5.3 Testing pipes from or in the field

To understand condition of pipes under real operating conditions, several field investigations were carried out on pipes in operation at various locations in Sweden. In total, 11 paired field measurements were performed on pipes in trenches or cut out pieces that were delivered to RISE facility, thanks to the energy companies who supported this project. The status of older supply DH pipes in operation was investigated in the sliding zones, where mechanical load on the insulation is assumed to be greatest, and the same pipes in the fixed zones, where mechanical load is assumed to be small/negligible. During the measurements, samples were also taken from the return pipes in case they would need to be used as a reference for the later analysis. The measurements were carried out using PipeOpsy™ method[12].

5.4 Evaluation methods

The pipes subjected to the laboratory conditions were evaluated following a time plan based on experience from the previous experiments. The frequency of data collection differed depending on the chosen conditions. Pipes in the field measurements were installed at different times and locations but were more than 20 years old. Evaluation methods used in this project were the SP plug method to study changes in the adhesion strength between PUR insulation and the service pipe, Fourier Transform Infrared (FTIR) spectroscopy to evaluate changes in the chemical structure of PUR and insulation capacity using Thermtest TLS-100 in accordance with ASTM D5334[16].

5.4.1 Adhesion strength

As explained in the introduction, one of the most crucial properties of the pipe design is good adhesion between the PUR insulation and the steel pipe. To quantify ageing effects with respect to this property, the SP plug method – method 5446 was used to measure changes in the shear strength. The method works so that a cylindrical test piece (plug) still being attached to the steel pipe is created within the pipe by a hole saw. In the next step an aluminium tube is glued to the plug. The test involves twisting the plug until it breaks while measuring the applied torque. The test rig is shown in Figure 4. At least three measurements were performed along the same pipe at each test occasion. After each test run, the pipes were restored by pushing prefabricated plugs of PUR into the holes followed by welding specially prepared HDPE discs to the casing see Figure 5.

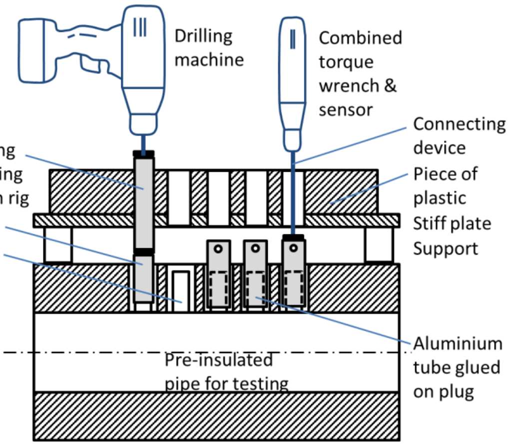

Figure 4: Measuring adhesion strength using the plug method

Figure 5: Restoration of a pipe after testing av adhesion strength

5.4.2 Chemical analysis

Fourier Transform Infra-Red (FTIR) spectroscopy has been chosen for chemical analysis because an infrared spectrum represents a fingerprint of a sample with absorption peaks which correspond to the frequencies of vibrations of the bonds between atoms making up the material. Since each material is a unique combination of atoms, no two compounds produce the exact same infrared spectrum.

Degradation of PUR leads to several alterations of its chemical structure. These can be analysed with advantage using FTIR[4,6] equipped with an ATR (Attenuated Total Reflectance) attachment. The principle of ATR involves passing of IR light through a crystal of a high refractive index material which reflects off the internal surface in contact with the test sample. The internal reflectance creates an evanescent wave which extends beyond the ATR crystal into the test sample which is in tight contact with the crystal. Only some specific frequencies of the light are absorbed by the sample while others pass through unaffected.

A detector measures what frequencies and how much of the light is absorbed by a material. This is recorded in form of an IR spectrum, that discloses what chemical bonds are present in a material and how the intensity of some bonds has changed because of chemical reactions. This method has been applied in current investigation to the plugs obtained from the adhesion strength measurements see Figure 6.

Two thin samples (1–2 mm) were taken from each plug for analysis, one from the end that has been in contact with the service pipe ("downside") and one from the opposite end ("upside"). The contact surface of the downside plug is the most degraded because it is exposed to the highest temperature, whereas the upside plug is located ~20 mm from the downside plug being consequently exposed to much lower temperature and is therefore regarded as the internal reference (not affected by ageing).

Figure 6: FTIR/ATR measuring of PUR

Our analysis was focused on quantifying changes in the urethane linkage, Figure 7: where the degradation begins. Reduction of intensities of the carbonyl peak C=O at around 1712 cm^{-1} and the N-H bending vibration peak at 1512 cm^{-1} which are both included in the urethane linkage were used as indicators of degradation, see Figure 8. The peak intensities were normalised by the intensity of the methylene diphenyl diisocyanate aromatic ring deformation (aromatic (C=C) vibration) at 1595 cm^{-1}, which is frequently used as the internal reference peak for each measurement.

To determine the degree of chemical degradation, an IR index was calculated as a ratio of the IR indexes from the downside and upside of a plug. A ratio of 1 means that no degradation has taken place, and the lower the value, the more a material is degraded.

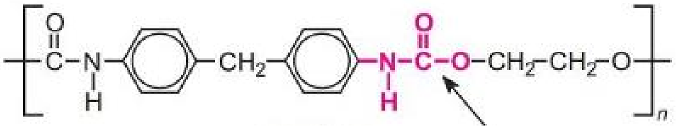

Figure 7: Chemical structure of polyurethane (PUR) (the part that is in purple is the urethane linkage)

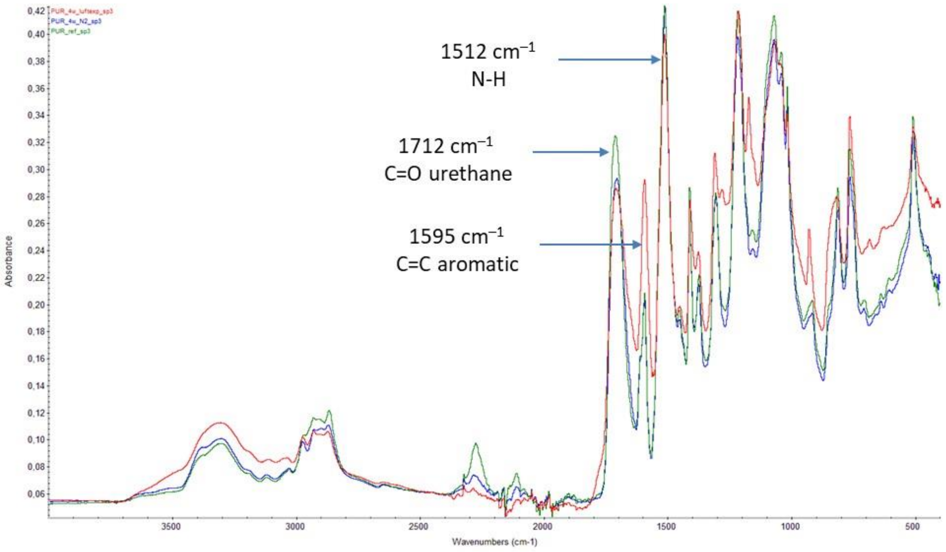

Figure 8: FTIR spectrum of polyurethane (PUR)

5.4.3 Thermal conductivity

Measurements of PUR foam thermal conductivity was performed using a Thermtest TLS-100 thermal conductivity meter, see Figure 99. This device consists of a hand-held unit to which a needle-shaped sensor, 100 mm long and 2 mm diameter, is connected. For each test, the entire needle sensor was pushed into the PUR foam using a hole in the external casing. This was coordinated with the adhesion strength testing, allowing the use of those test location to be used also for thermal conductivity testing.

This approach limited the number of openings made in the pipe casing and strengthens the use of the methods in tandem. The needle was always inserted in the PUR foam at an angle so that no part of the needle was closer than 5 mm to the service pipe, and the tip of the needle did not reach the casing on the opposite side. Before each experiment, frictional heat generated by pushing the needle into the foam was allowed to dissipate. A 10-minute waiting period was found to be adequate to reach stationary temperature.

During each experiment the needle was gently heated by a constat effect for 90 s and the resulting temperature increase as a function of time was recorded. The temperature increase was limited and did not exceed 10 °C for any accepted test. Temperature rise was also required to be above 2 °C after each test. This temperature rise interval ensures best possible data. It should be noted that also a 90 s cooling sequence was recorded during each experiment but not further used.

The value of the thermal conductivity of the sample was then extracted from the transient temperature increase vs time data using the fact that it is proportional to the inverse of the slope of the linear part of the curve. The thermal conductivity can be calculated from the experimental data using the following simplified equation:

$$\lambda = \frac{CQ}{4\pi S} \tag{10}$$

where λ is the thermal conductivity, C is the sensor calibration factor, Q is the effect per unit length in the sensor and S is the slope of the linear part of the temperature increase plotted as a function of the logarithm of the measurement time. The calibration factor C for the TLS-100 is determined by the manufacturer, and all calculations are done directly in the instrument's supplied software. The method is described in detail in ASTM standard D5334-14, but calibration is in this case performed using low conducting materials with similar properties as PUR foam, to find a C value that is valid for thermally insulating materials.

One to three tests were performed at each needle position. Multiple tests allow the calculation of an average thermal conductivity and standard deviation to confirm test stability. Data quality was verified with the correlation factor given by the device. This value shall be close to unity to ensure a good match between the line fitting and the raw experimental data. Test locations were never reused and fresh openings in the casing were used for all tests. Each sample, as specified in Table 1, was tested multiple times in conjunction with adhesion strength testing. Samples with diffusion barrier were tested only once.

Figure 9: Measurement of thermal conductivity in a DH pipe

6 Results and discussion

A previous study[9] has clearly shown that mechanically stressed pipes degrade significantly faster during thermal ageing than pipes aged at the same temperature without mechanical shear stress. The FTIR study revealed also that this effect is due to a significantly faster chemical degradation of the PUR foam when the pipes were mechanically stressed during the thermal ageing.

One of the main objectives of the current project was to study long term effects of cyclic mechanical loads on the rate of degradation using different stress levels and cycle periods during thermal ageing at the highest possible temperature. Another goal was to investigate how pipes manufactured with different production methods and pipes with a gas barrier are affected under these conditions. Finally, a series of field measurements were carried out with the aim of clarifying whether this relationship also exists under real operating conditions.

In sections 6.1 to 6.4 the results of thermal, mechanical and thermo-mechanical accelerated laboratory ageing tests of both Disconti. and Conti. pipes are presented, compared and discussed. In sections 6.5 and 6.6 a summary of the results of mechanical and chemical tests on the pipes in the field are presented and discussed. For the pipes in the field a recalculation of their real operating periods with varying operating temperatures was made to an equivalent operating time at the reference temperature of 95 °C. The temperature profiles of operation temperatures of each pipe investigated were provided by the energy companies.

The recalculation of installation age makes it possible to compare the age of different pipelines from different networks and operated using different temperature profiles. The recalculation was done based on 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 according to the pervious investigation[12]. The principle of recalculation is based on the assumption that when the operating temperature is increased by 10 °C, the chemical reactions are assumed to proceed *Af* times faster.

6.1 Accelerated ageing of Disconti. pipes

In all the previous laboratory studies conducted at RISE, custom-made Disconti. pipes with the least possible variation in density and other structural properties were used. In this study, pipes from regular production were used. An important difference compared to the previous pipes is a significantly greater variation in properties in the pipes examined. To determine the extent of the variation in the initial value of the adhesion strength, a series of measurements of the adhesion strength were carried out along and around the unaged reference pipe. The results are summarised in Table 4 with test location indicated with capital letters and degrees of rotation around the pipe, see Figure 10.

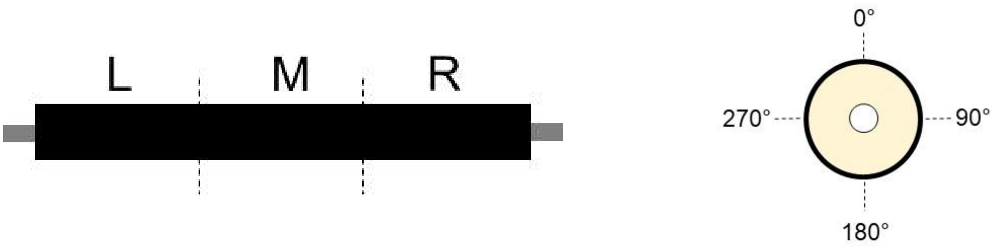

Figure 10: Sketch of where adhesion strength measurements have taken place

Table 4: Results of adhesion strength measurements using RISE plug method on a Disconti. reference pipe, as recorded at different locations on pipe according to Figure 10 (numbers at the bottom in bold are averages)

Unit	L (0°)	M (0°)	R (0°)	L (90°)	M (90°)	R (90°)
[Nm]	1,84	2,54	3,06	1,35	3,12	1,72
[Nm]	2,78	2,24	3,07	1,39	2,93	1,89
[Nm]	2,60	2,14	2,83	1,79	2,89	1,84
Nm	**2,41**	**2,31**	**2,99**	**1,51**	**2,98**	**1,82**
MPa	**0,62**	**0,60**	**0,77**	**0,39**	**0,77**	**0,47**

	L (180°)	M (180°)	R (180°)	L (270°)	M (270°)	R (270°)
[Nm]	2,24	2,82	2,43	1,57	2,13	2,53
[Nm]	2,35	2,32	2,35	1,63	1,27	2,54
[Nm]	2,27	2,51	2,24	2,38	1,57	2,47
Nm	**2,29**	**2,55**	**2,34**	**1,86**	**1,66**	**2,51**
MPa	**0,59**	**0,66**	**0,61**	**0,48**	**0,43**	**0,65**

The average of all measurements taken as reference value was determined to be 2,27 Nm and calculated to 0,59 MPa (see appendix 1) but the spread of results is very large, e.g. the difference between the lowest and the highest average initial value is about a factor of two.

For comparison, the demand of shear strength between unaged PUR and the steel pipe given in EN 253 is 0,12 MPa measured using the axial shear strength method. In this study, the adhesion strength was measured using the SP plug method – method 5446. According to the previous investigation the value 0,12 MPa in EN 253 corresponds to about 0,36 MPa when measured with the plug method[17]. Variations in density were also measured on the same pipe with similar variation of results where the lowest values were around 50 kg/m^3 while the highest were close to 80 kg/m^3.

Results of adhesion tests after various ageing periods on Disconti. pipes are presented in Figures 11 and 12 where a red horizontal line indicates the lowest measured starting mean value (from unaged reference pipe) while the green line indicates the highest measured starting mean value (from unaged reference pipe). Figure 11 summarizes results from three Disconti. pipes after prolonged exposure: one exposed to the highest mechanical stress at room temperature P1A, one exposed to the highest mechanical stress at 140 °C P2C and one exposed to 140 °C P1D without mechanical stress.

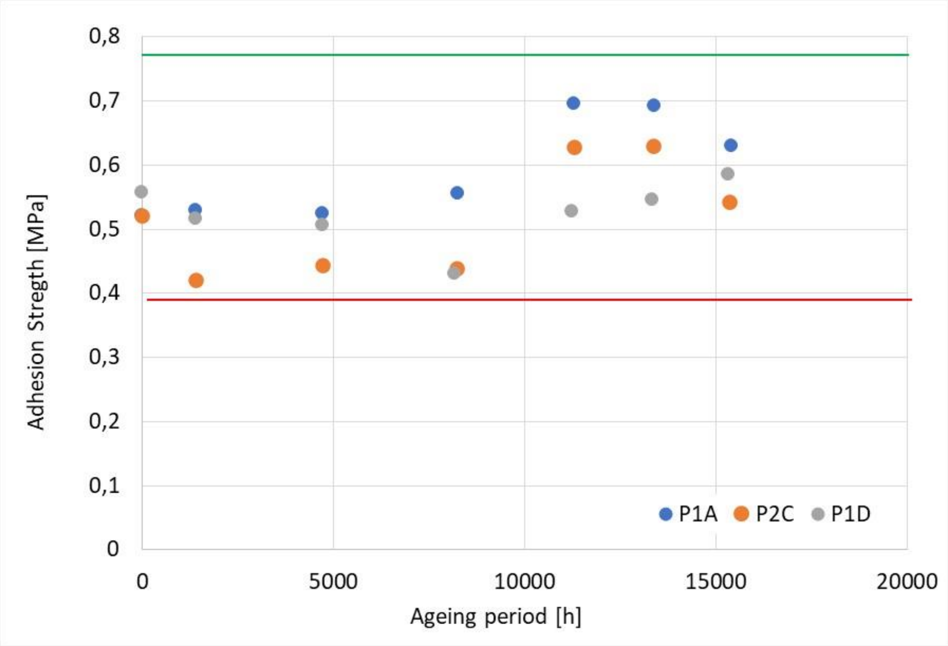

Figure 11: Adhesion strength as a function of ageing time for pipes P1A (23/25/30), P2C (140/25/30) and P1D (140/-/-) where numbers in brackets indicate temperature/load/cycle time.

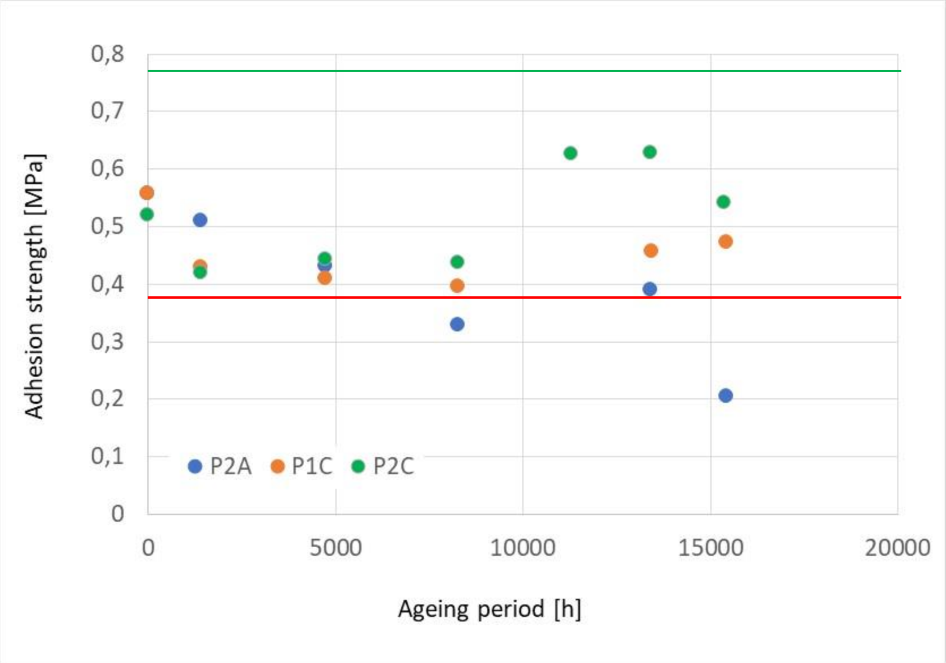

Figure 12: Adhesion strength as a function of ageing time for pipes P2A (140/25/60), P1C (140/8/60) and P2C (140/25/30) where numbers in brackets indicate temperature/load/cycle time.

The results clearly show that none of the exposures up to 16 000 h have affected the adhesion strength of the pipes. It is worth noting that this time corresponds to about 75 years of operation at 95 °C (see section 5.2).

Figure 12 summarizes results from three Disconti. pipes after prolonged exposure to 140 °C under different stress conditions: one exposed to the highest mechanical stress and long cycle period P2A, one exposed to the highest mechanical stress and short cycle period P2C and one exposed to the lowest mechanical stress and long cycle period P1C. The results show that after 16 000 h of ageing only the pipe exposed to the highest mechanical stress and long cycle exhibits a clear decrease in adhesion strength (see Figure 12).

Already in a previous study, we have shown the benefit of using IR spectroscopy to discover degradation before significant reduction in adhesion strength occurs[9]. IR analyses can reveal early signs of degradation even though the adhesion strength remain unchanged. This is the case here as well. In Figure 11 and 12 it is shown that the exposures up to 16 000 h have not affected the adhesion strength of the pipes investigated with one exception. However, IR analyses of these pipes have clearly shown that the PUR in all the pipes exposed to different stresses and cycle periods at 140 °C has started to degrade as can be seen in IR analyses as the reduction of peak intensity at 1712 cm^{-1} (see Figure 13 and 15).

The first sure signs of degradation occur already after 10 000 hours of ageing. IR analyses at 1512 cm^{-1} are slightly less sensitive to degradation but despite that, signs of degradation are confirmed for this peak as well (see Figure 14 and 16) for all pipes exposed to combine effect of mechanical stress and thermal ageing. The pipe aged at 140 °C without mechanical load showed a first sign of degradation after about 15 000 h as a minor reduction of the 1712 cm^{-1} peak but no change in the 1512 cm^{-1} peak.

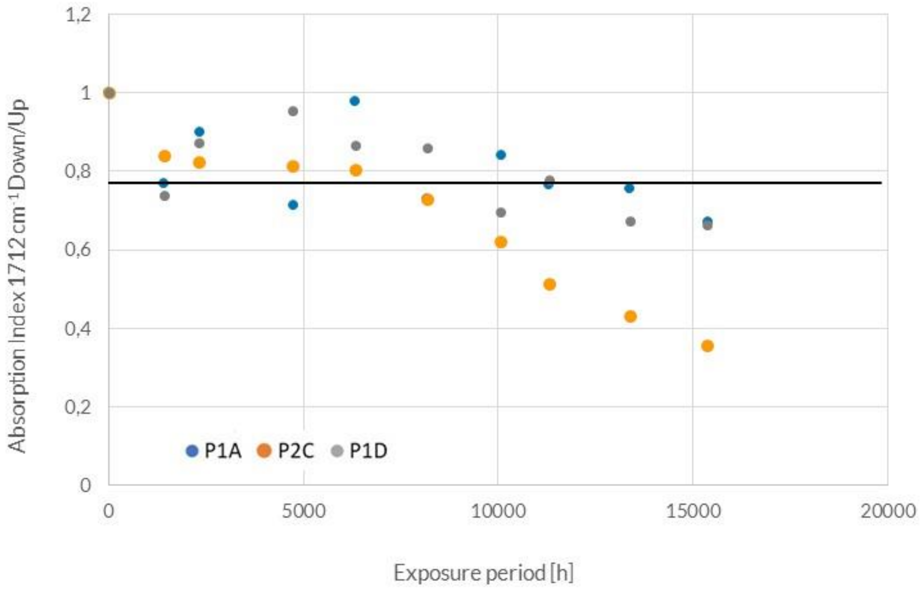

Figure 13: IR absorption index at 1712 cm^{-1} as a function of ageing time for pipes P1A (23/25/30), P2C (140/25/30) and P1D (140/-/-) where numbers in brackets indicate temperature/load/cycle time. The horizontal black line means that data points below this line indicate degradation.

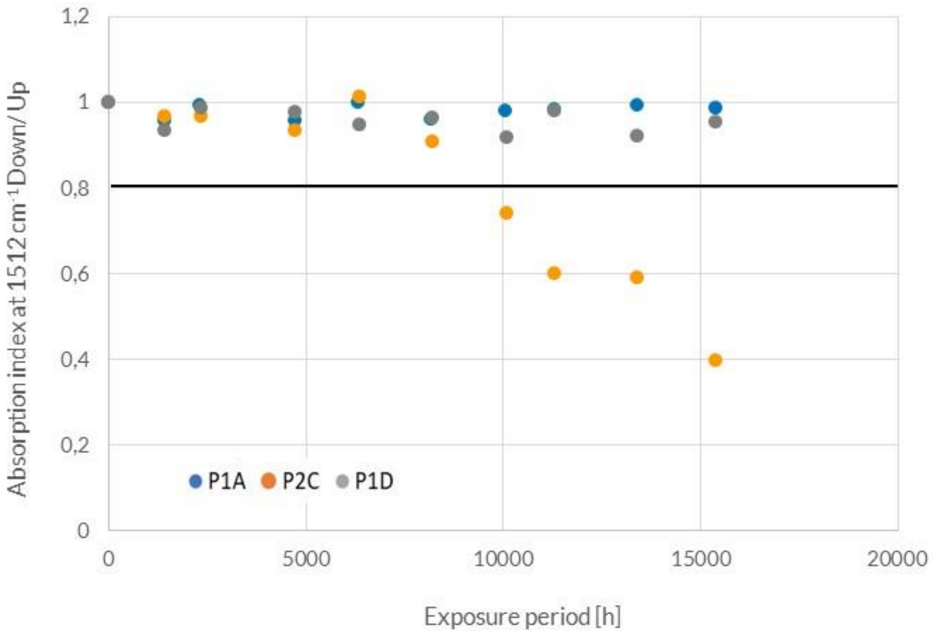

Figure 14: IR absorption index 1512 cm^{-1} as a function of ageing time for pipes P1A (23/25/30), P2C (140/25/30) and P1D (140/-/-) where numbers in brackets indicate temperature/load/cycle time. The horizontal black line means that data points below this line indicate degradation.

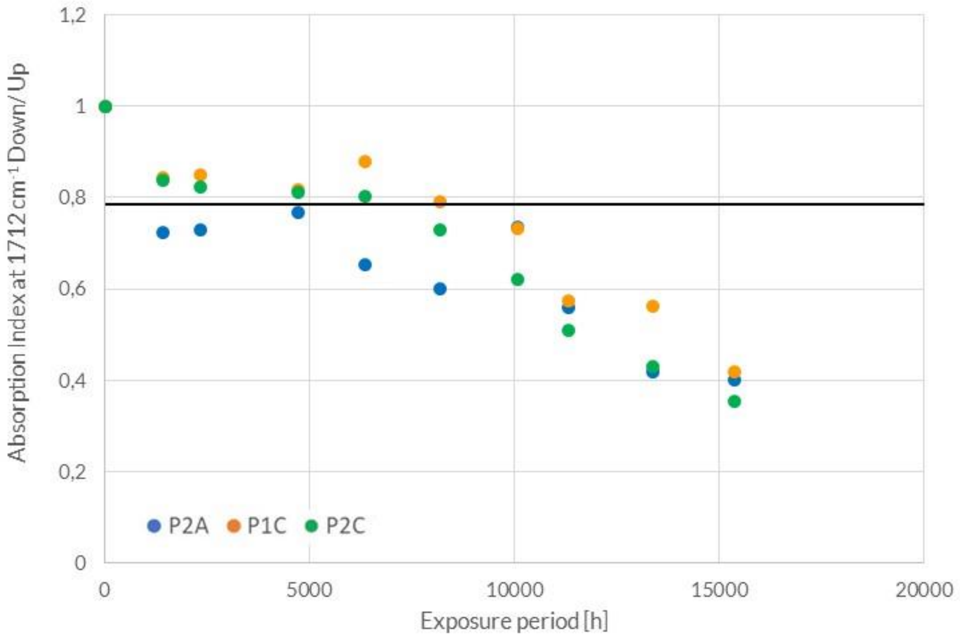

Figure 15: IR absorption index at 1712 cm^{-1} as a function of ageing time for pipes P2A (140/25/60), P1C (140/8/60) and P2C (140/25/30) where numbers in brackets indicate temperature/load/cycle time.

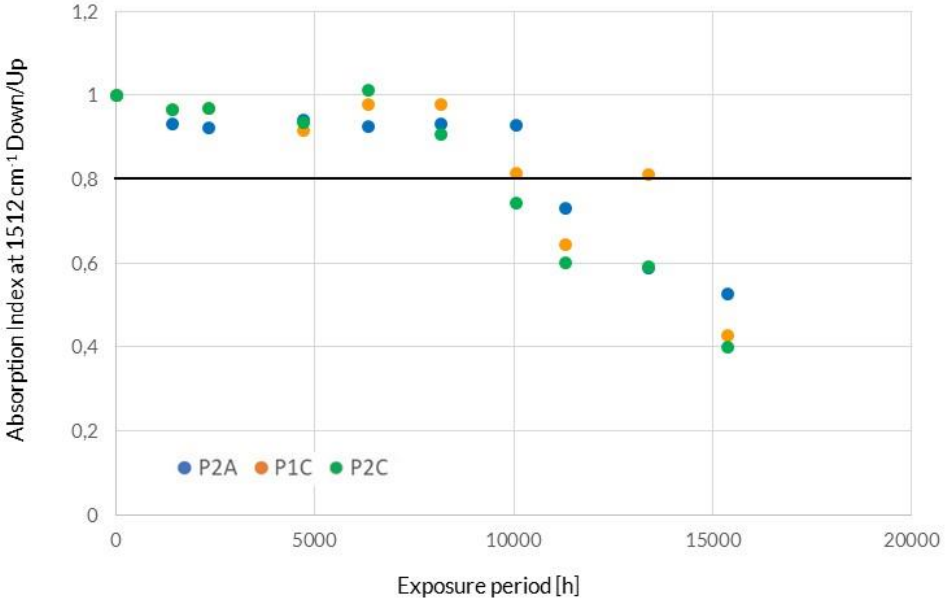

Figure 16: IR absorption index at 1512 cm^{-1} as a function of ageing time for pipes P2A (140/25/60), P1C (140/8/60) and P2C (140/25/30) where numbers in brackets indicate temperature/load/cycle time.

In Figure 12 it was shown that of three Disconti. pipes exposed to 140 °C under different stress conditions only the pipe exposed to the highest mechanical stress and long cycle exhibits a significant decrease in adhesion strength. However, IR analyses have clearly shown that PUR insulation in all three pipes has begun to degrade. The first signs of degradation are show by the pipe P2A (the highest stress and long cycle) after about 6 000 h followed by P2C (the highest stress and short cycle) after about 8 000 h and finally P1C (the lowest stress and short cycle) after about 10 000 h (see Figure 15).

6.2 Accelerated ageing of Conti. pipes

In this study, pipes manufactured using a continuous method (Conti. pipes) were used as well to determine whether there is any difference in how these are affected by ageing compared to Disconti. pipes. In addition, Conti. pipes with gas barrier were also investigated. Also in this case, an investigation was carried out regarding the variation of the adhesion strength along and around an unaged pipe.

An average value of all measurements taken from unaged Conti. pipe was determined to be 2,07 Nm or 0,54 MPa (see Table 5) which means slightly lower adhesion strength compared to Disconti. pipes. However, the significant difference between the two types of pipes lies in the variation of adhesion strength along and around pipes. While the spread of results for the unaged Disconti. pipes are from -34 % to +30 % calculated from the average value, the corresponding numbers for the unaged Conti. pipes are -13 % to +15 %.

Table 5: Results of adhesion strength measurements on a Conti. reference pipe, as recorded at different locations along and around (numbers at the bottom in bold are averages)

	L (0°)	M (0°)	R (0°)	L (90°)	M (90°)	R (90°)	L (180°)	M (180°)	R (180°)
[Nm]	1,97	2,17	1,87	1,78	2,03	1,80	2,01	2,31	2,37
[Nm]	1,99	2,26	1,88	1,83	1,96	2,01	2,26	2,43	2,32
[Nm]	2,11	2,29	1,92	1,83	1,86	1,97	2,01	2,41	2,29
Nm	**2,02**	**2,24**	**1,89**	**1,81**	**1,95**	**1,93**	**2,09**	**2,38**	**2,33**
MPa	**0,52**	**0,58**	**0,49**	**0,47**	**0,50**	**0,50**	**0,54**	**0,62**	**0,60**

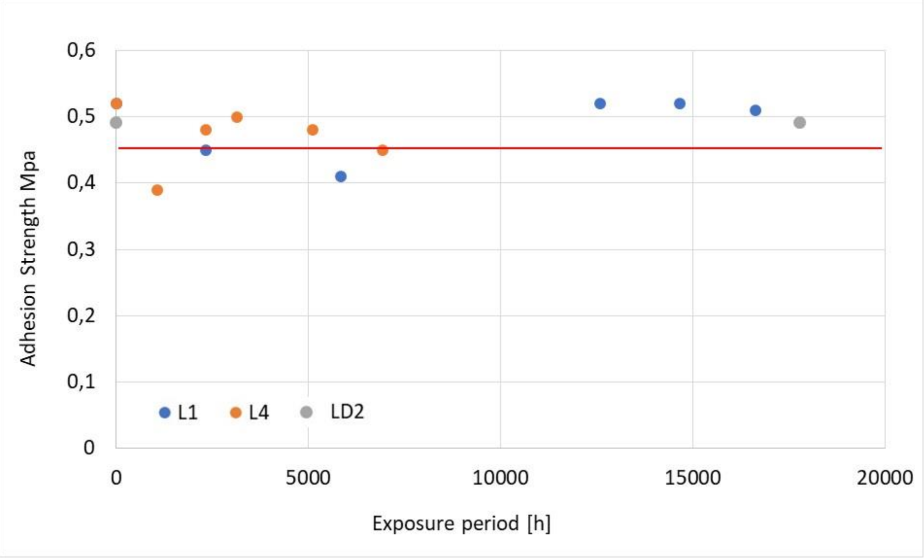

Figure 17: Adhesion strength as a function of ageing time for the Conti. pipes L1 (140/25/30), L4 (140/-/-) and the Conti. pipe with gas barrier (140/25/30) where numbers in brackets indicate temperature/load/cycle time.

Results of adhesion tests on Conti. pipes after periods of exposure to different ageing conditions are presented in Figure 17. The values for Conti. pipe with barrier originate from two pipes, one was unaged, and the other one was exposed to fulltime ageing.

Accelerated ageing has been performed for up to 18 000 hours without any signs of reduction in adhesion strength (see Figure 17).

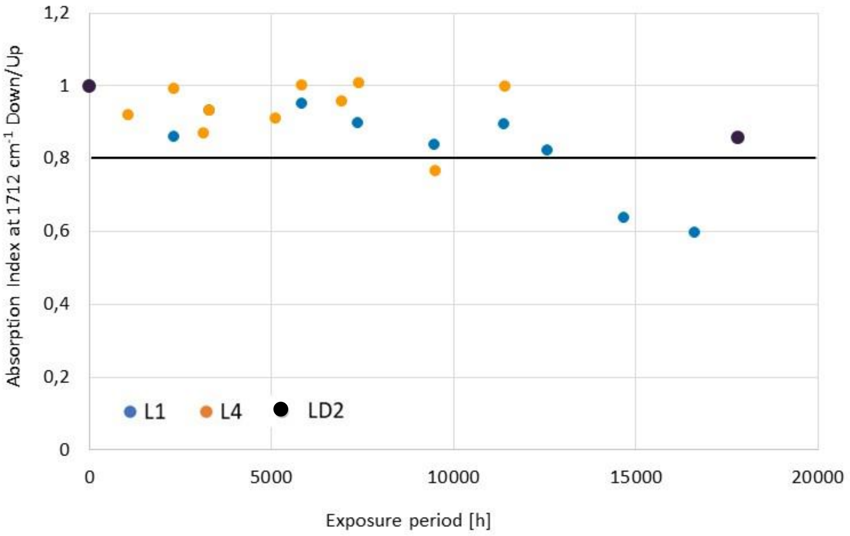

Figure 18: IR absorption index at 1712 cm^{-1} as a function of ageing time for Conti. pipes L1 (140/25/30), L2 and L4 (140/-/-) and LD2 (140/25/30) where LD pipe had diffusion barrier and numbers in brackets indicate temperature/load/cycle time.

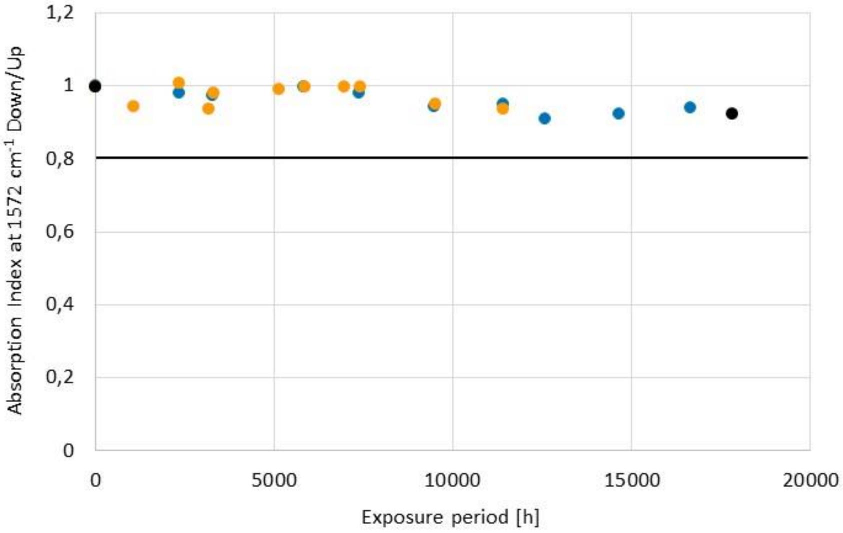

Figure 19: IR absorption index at 1512 cm^{-1} as a function of ageing time for Conti. pipes L1 (140/25/30), L2 and L4 (140/-/-) and LD2 (140/25/30) where LD pipe had diffusion barrier and numbers in brackets indicate temperature/load/cycle time.

In Figure 17 it is shown that there are no signs of reduction in adhesion strength after 18 000 h of exposure to 140 °C whether with or without load (L1 and L2). However, in the IR analyses there is a clear sign that the pipe exposed to both high temperature and mechanical stress has started to degrade after 14 000 h (see Figure 18). The similar pipe LD 2 containing gas barrier exposed to the same ageing conditions has not shown any signs of degradation up to 18 000 h of ageing. IR peak at 1512 cm^{-1} which is slightly less sensitive to degradation reveals no signs of degradation (see Figure 19).

6.3 Accelerated ageing by cyclic temperature variations

In this specially designed experiment, axial stresses were created only by alternating the temperature between 30 and 140 °C. Stress is created because PUR has a coefficient of linear expansion approximately 5 times greater than steel. Only one Disconti. pipe was used in this experiment for prove of concept. Changes in adhesion strength are presented in Figure 20 as a function of ageing time at 140 °C. Time at 30 °C is not included as it is known from previous studies that no degradation occurs at such a low temperature. Unfortunately, the experiment had to be terminated prematurely due to a failure in the control system. Results of IR analyses are presented in Figure 21 and Figure 22.

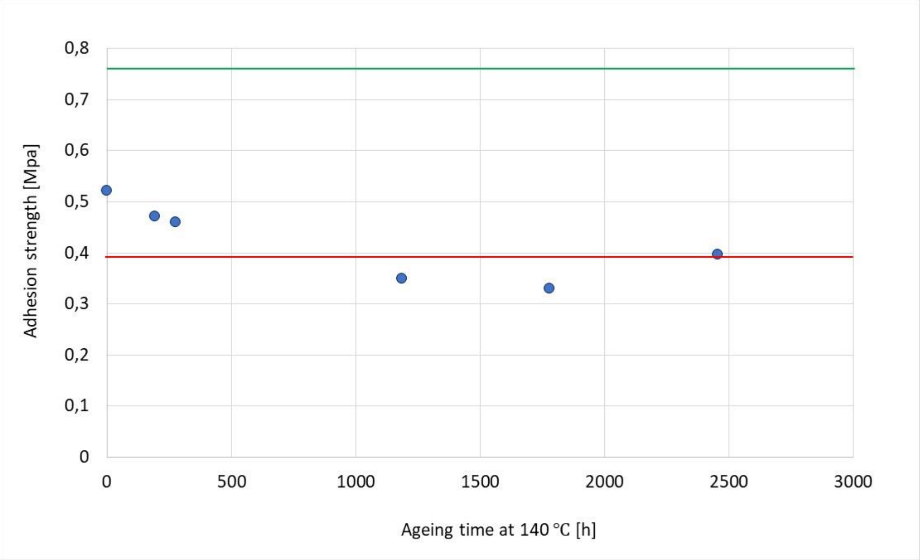

Figure 20: Adhesion strength vs ageing time at 140 °C.

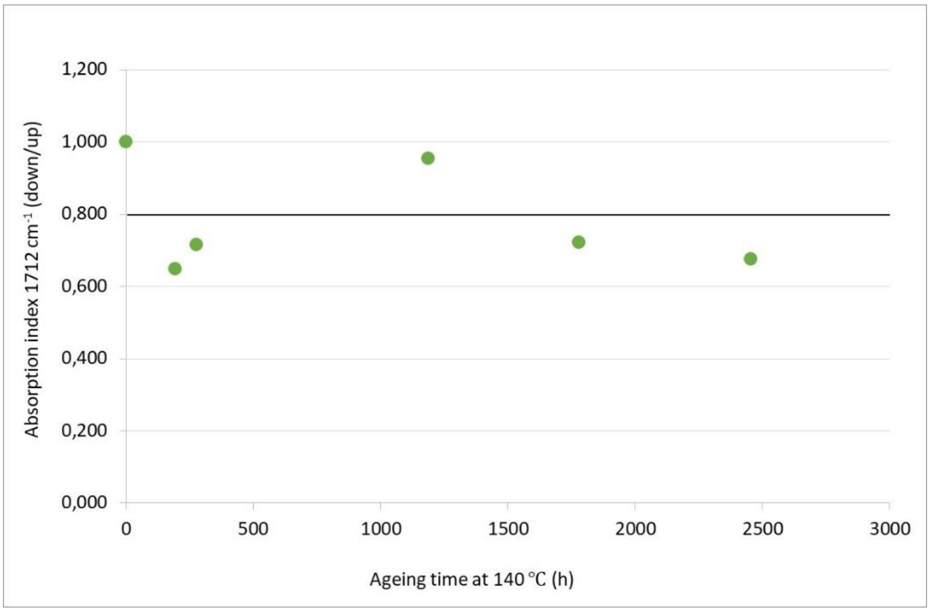

Figure 21: IR absorption index at 1712 cm^{-1} as a function of ageing time at 140 °C.

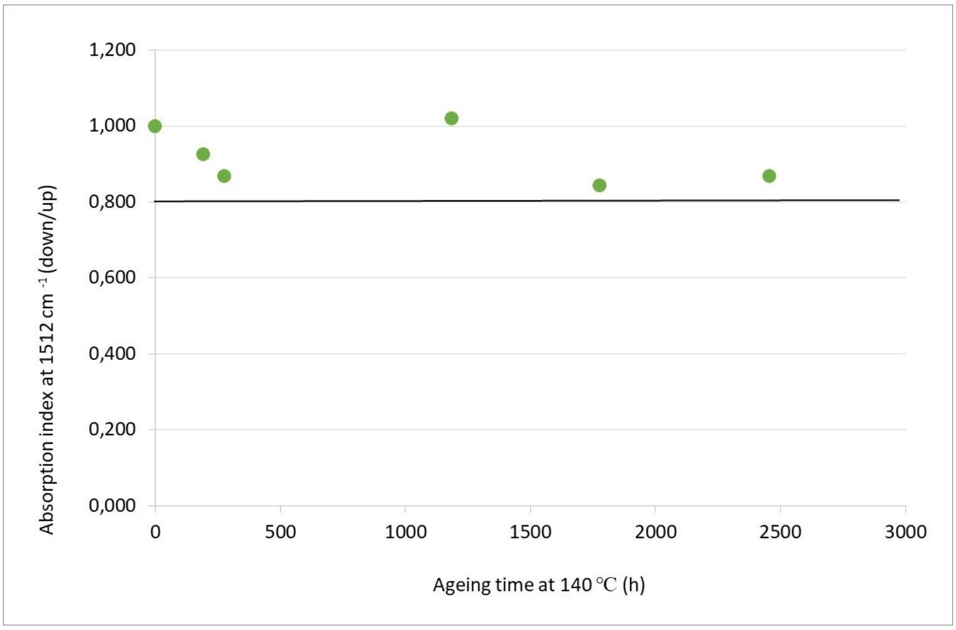

Figure 22: IR absorption index at 1512 cm^{-1} as a function of ageing time at 140 °C.

The initial results seem promising, but no conclusions can be drawn because the ageing time was too short. A new experiment is planned with improved steering and control.

6.4 Thermal conductivity measurements

As a complement, a series of thermal conductivity measurements were performed in conjunction with adhesion tests where plug holes were used to insert the measuring needle. The thermal conductivity results have here been normalized using the reference value of Conti. and Disconti. pipes respectively. This allows the study of trends and internal variation rather than triggering a discussion about the absolute thermal conductivity values. It shall here be noted that the thermal conductivity measured was in all experiments in the range of 0,023 to 0,026 W/m/K.

The main conclusion from these tests is that the method shows stable and coherent results. All samples show a slow increase in the thermal conductivity over time. Based on linear trend-lines, the increase is in the range of 3 to 6 % for all samples. It is also concluded that there is a larger spread between and with individual Disconti. samples, as seen from the R^2 values, averaging 0,69 as compared to 0,83 for Conti. pipes. The larger spread for Disconti. samples is attributed to the inherent variation in density of the PUR foam, which varies along the pipe length and from top to bottom due to the production method.

The reason for the increase of thermal conductivity is explained by a slow gas exchange in the cells of the PUR foam. CO_2 is over time replaced by air and the thermal conductivity will increase until air has fully replaced the CO_2. Once this process is completed, the thermal conductivity is expected to reach a plateau value for the duration of the service life of the pipe, assuming that the pipe is not in any other way damaged. During these tests the plateau level was not reached. Longer test times would have been required for this phenomenon to occur.

The minor differences between samples are most likely because even with a service pipe temperature of 140 °C, the temperature in the foam, and most importantly at the casing, is closer to the ambient temperature of the laboratory. Consequently, the ageing factor is here much lower than the factor that can be applied to the foam/service pipe interface. It is noted that no significant difference between the Conti. pipes with and without diffusion barrier could be detected at the time scales of this project. A significantly longe elapse time of the experiment would have been needed to fully explain and explore this.

It is further concluded that thanks to the stable nature of the data, the method is suitable for monitoring of PUR foam insulation quality and can be used to detect irregularities, such as mechanical or water damage to the structure. Below, measurement data normalised using the refence sample for Disconti. and Conti. pipes respectively are presented. For each data set, a straight line fit and corresponding R^2 value is presented.

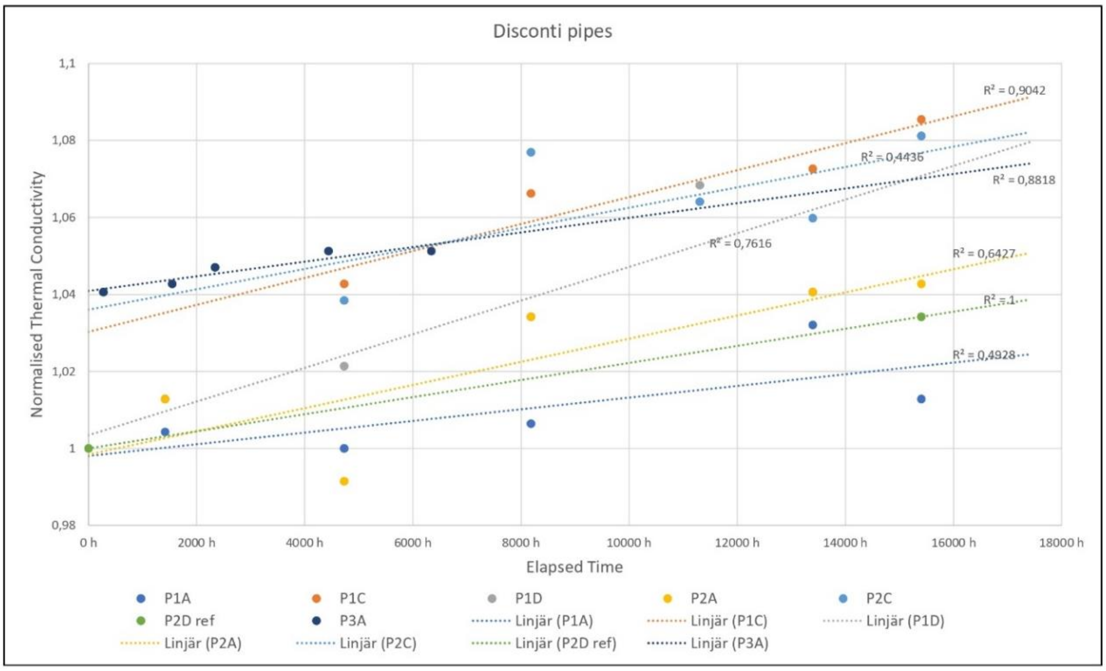

Figure 23: Normalised thermal conductivity of Disconti. pipes. The trend is similar between the pipes, but there is noticeable difference in the base thermal conductivity between the samples.

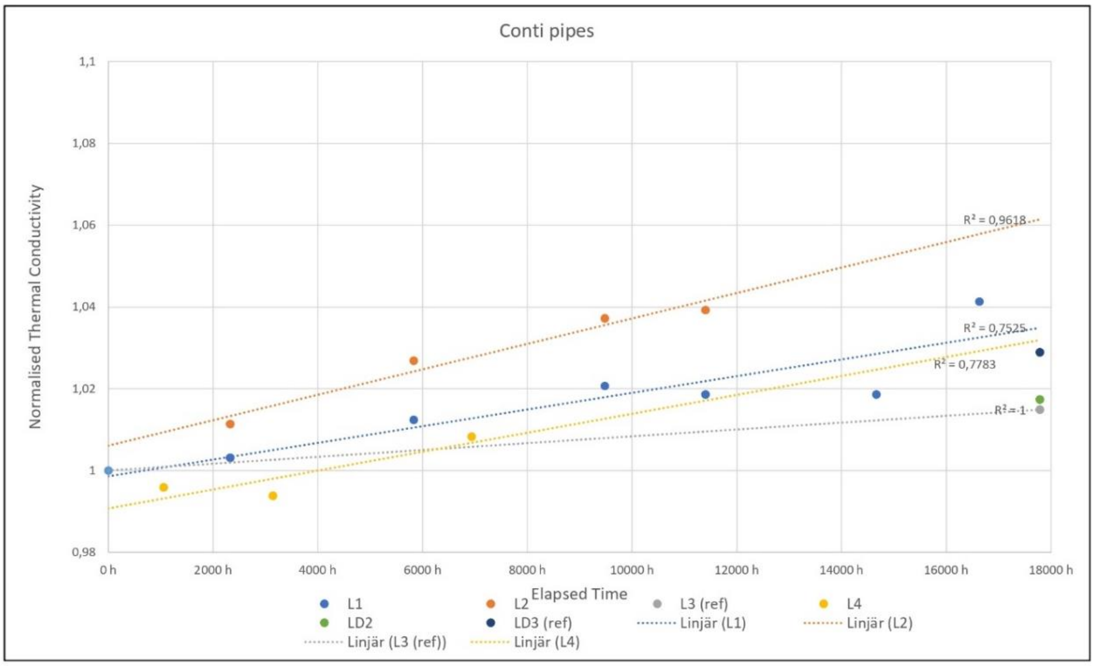

Figure 24: Normalised thermal conductivity of Conti. pipes. The trend is similar between the pipes, and the base level is also similar between samples.

6.5 Summary of field measurements – fix vs sliding zone

In the parallel project entitled “Effects of mechanical loads on ageing of district heating pipes” which was also a part of this project, old, naturally aged DH pipes still in operation were examined. The focus of this study was to find out whether parts of pipes subjected to mechanical shear loads in sliding zones have aged faster than the parts in fix zones of the same pipe where mechanical loads are negligible.

For this purpose, eleven pipes were chosen for tests with two positions on each pipe viz. one in the sliding zone, and one in the fixed zone. The results of the field tests are presented in Figure 25 (shear strength), Figure 26 (FTIR) and Figure 27 (FTIR). Adhesion strength measurements were performed in the field on pipes during operations or on cut pipes at the laboratory using the RISE plug method and chemical analysis by FTIR.

According to EN 253 an axial shear strength test is usually used for measuring of adhesion strength and a limit value was estimated to be 0,04 MPa. Through correlation studies[17], 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.

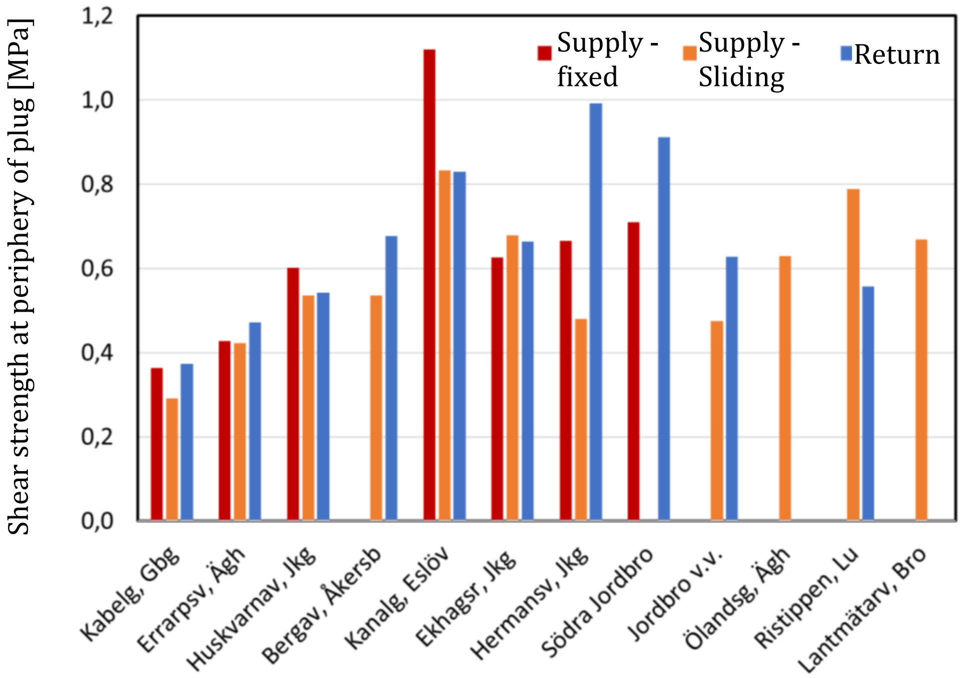

Figure 25: Shear strength for pipes at various location in Sweden

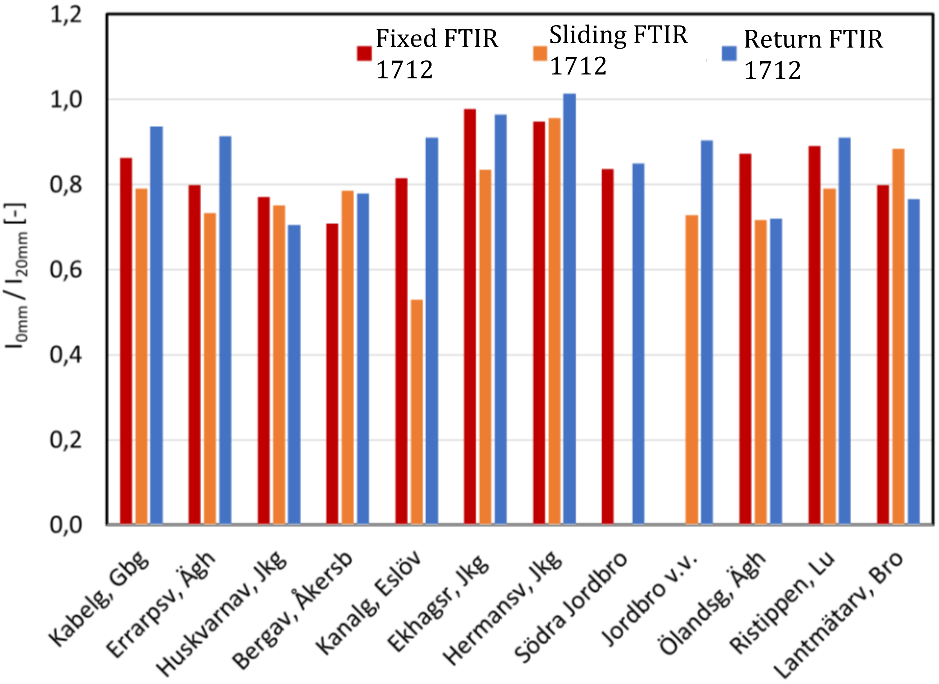

Figure 26: Index for 1712 cm^{-1} (Bond C=O in Urethane group) for the different locations of the pipes at various location in Sweden

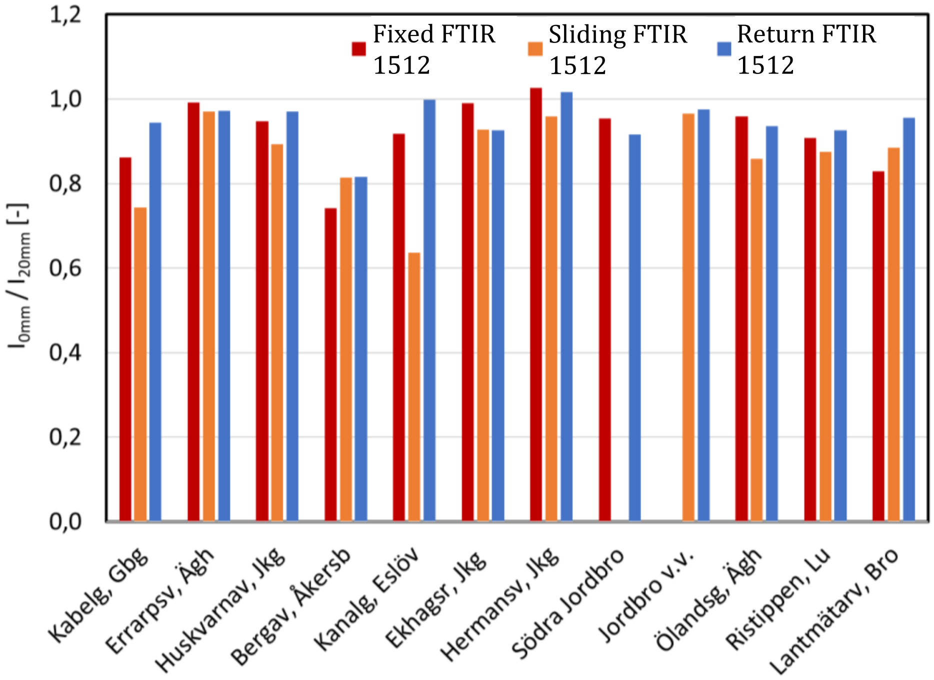

Figure 27: Index for 1512 cm^{-1} (Bond N-H in Urethane group) for the different location of the pipes at various location in Sweden

The results from this part of the project are described in more detail in the report[18]. The results obtained from the study have also been used in probability calculations which led to the following conclusions:

- the adhesion strength in the fixed zone is greater than in the sliding zone with 93 % confidence.
- the IR indices in the fixed zone are greater than those in the sliding zone with 97,5 % confidence.

From these probability calculations, it is reasonable to conclude that field measurements confirm the conclusion from the laboratory experiments that pipes where the insulation is subjected to varying shear stress age faster than pipes without shear stress.

7 International cooperation

The project results have been presented to the market and academia outside Sweden, which has placed Swedish district heating research at the forefront of the international arena.

7.1 Collaboration with IEA- DHC Annex projects

Most of the international collaboration has taken place through participation in two IEA-DHC Annex projects viz. Annex Task Share 6 (TS 6), and Annex Task Share 8 (TS 8). The idea for starting of TS 6 project with the title "Status assessment, ageing, lifetime prediction and asset management of District Heating Pipes" was based on research findings from RISE in Sweden, HCU and AGFW in Germany. The project started in 2022 and consists of subtasks dealing with status assessment, accelerated ageing tests for study of degradation, lifetime estimation, asset management and future perspectives of district heating networks.

Many researchers and energy companies from other countries such as South Korea, Belgium, Polen, Italy, Denmark, the Netherlands and China have joined the project to explore and connect their research work to each other. For four years the results of research have been discussed at meetings and workshops. Recently a Round Robin test has started to evaluate a new proposed test method. Challenges for existing and future generations of DH pipes have been identified. The project will be finished in the end of 2025. Preliminary results of all subtasks have already been presented in China, US and recently at IEA-DHC symposium in Genk.

Another international collaboration project is with TS 8 with title "Experimental investigations of DHC systems". The project started with an invitation to RISE research group from Fraunhofer Institute in 2024 to participate in the project. The goal of TS8 is to prove new DHC supply strategies, laboratory investigations and field experiments in conjunction with software-based and digitized applications (e.g., digital twins) for enhancing and improving the performance of DHC systems and support the necessary expansion of DHC supply.

With the help of experimental investigations, more flexible investigations are possible. TS 8 project consists of subtasks (ST) where RISE role is to lead ST D "Derivation of conceptual guidelines for experimental design setups and to draw conclusions from gathered data and identify any required open research issues" and to contribute to the experimental work. Collaboration mostly takes place through meetings within Core-Group and though Working Phase Meetings.

8 Project management, administration and communication

The work of this WP was to ensure efficient time and quality management of the project through administrative and scientific project coordination. The objectives were to coordinate, structure and oversee collaboration between partners as well as implementation of activities, completion of goals and timely production of deliverables. The aim was also to facilitate participative decision making, by providing a platform and forum for communication between partners, across WPs. The focus was on support, providing tools and guidelines related to data management, ethics management, risk and quality management. To facilitate coordination and progress monitoring, the following activities were performed:

- Constitution of the project executive group, project group
- Collaboration with FutureHeat reference group for WP3
- Mail conversation with all partners to provide information regarding the project management structure, processes, stakeholders as well as upcoming meetings and other events
- Set up file sharing service for data storage and exchange
- Organization of meetings to facilitate frequent exchange and discussions of synergies between WPs and their results and achievements.
- Annually Status and economic reporting to the Swedish Energy Agency as main financer

9 Conclusions

In this study, pipes from regular production were used. It was therefore important to investigate how the properties vary along and around in these pipes. Two properties were investigated, namely adhesion strength and density. Regarding adhesion strength, a significantly greater variation was measured in Disconti. pipes compared to Conti. pipes. While the spread of adhesion strength for the Disconti. pipes were from -34 % to +30 % from the average value, the corresponding results for the Conti. pipes were -13 % to +15 %.

In the present investigation, the main goal was to study the effects of repetitive axial loads on the rate of thermal degradation of DH pipes produced using different methods. Long-term ageing was performed at 140 °C with two different mechanical loads and two cycle periods. For comparison, ageing was also performed at the same temperature but without mechanical loading and in addition an exposure to mechanical loading at room temperature. The maximum ageing time was 16 000 h for Disconti. pipes and 18 000 h for Conti. pipes, which is estimated to correspond to 75 and 84 years, respectively, at an operating temperature of 95 °C.

Measurements of the most important property, namely adhesion strength, showed no changes after the total ageing period except for one Disconti. pipe exposed to the highest mechanical stress and long cycle period which showed a first sign of decline after 16 000 h. Based on the measurements of adhesion strength, no relationship can be established between exposure parameters and degradation rate or calculation of expected service life. To be able to do this, a significantly longer ageing time would be needed so that a clear reduction in adhesion strength could be observed. A conclusion that can be drawn is that the investigated pipes have a service life exceeding 75 years at an operating temperature of 95 °C even under the influence of high repetitive axial loads.

It is known from previous studies that IR analysis can reveal the onset of degradation significantly earlier than adhesion strength measurements. For Disconti. pipes exposed to the combined effect of mechanical load and high temperature, the first signs of degradation are visible after about 6 000 h for the pipe exposed to the highest stress and long cycle followed by the pipe exposed to the highest stress and short cycle after about 8 000 h and finally the pipe exposed to the lowest stress and short cycle after about 10 000 h as indicated by the reduction in peak intensities at 1712 and 1512 cm^{-1}. For the pipe exposed to high temperature only, the first sign becomes visible after 15 000 h at 1712 cm^{-1} only.

The first sign of degradation for the Conti. pipe exposed to both high temperature and mechanical shear stress appears after 14 000 h and is only visible as reduction of 1712 cm^{-1} peak intensity. It is interesting also to note that the similar pipe with gas barrier exposed to the same treatment show no signs of degradation even after 18 000 h.

To summarize, the effect of different loads and cycle periods on the degradation rate can only be evaluated here using results from IR measurements after various ageing periods. Although the results suggest that the pipe exposed to the highest load and the longest cycle period degrades the fastest and the pipe with the lowest load degrades the slowest, the differences are small.

The status of older DH pipes in operation was investigated to find out whether an effect of mechanical shear loads exists under real operating conditions similar to laboratory studies. Several pipes were tested in the field. The tests were conducted at two different locations on the same pipe namely in the sliding zone, where mechanical load on the insulation is assumed to be the greatest, and in the fixed zone, where mechanical load on the insulation is assumed to be small/negligible. The conclusion from the field measurements is that these results confirm the agreement with the laboratory studies namely that the degradation is greater in the sliding zone than in the fixed zone with a probability of 97,5 % based on IR measurements.

As a complement, a series of thermal conductivity measurements were performed on the same DH pipes exposed to various ageing conditions. However, while the degradation rate in PUR was accelerated in our experiments by a factor of 41, the acceleration factor of the gas exchange that is crucial for changes in thermal conductivity was only 2. The main conclusion from these tests is that the method shows stable and coherent results. All samples show a slow increase in the thermal conductivity over time. Based on linear trendlines, the increase is in the range of 3 to 6 % for all samples.

10 Lessons learned

Prerequisites, assumption and boundaries in this investigation have limited this study and the outcome of it. According to our knowledge such an investigation has not been performed anywhere before in this form and scale. The set up and rig were built from scratch, and some learnings lessons we got during the project time. The prerequisites were not optimal when we started the project. There were delays of production and transports after the pandemic, when we ordered necessary equipment for the set-up of our rigs.

Our plans for scientific work and the background assumptions were based on the literature and our earlier investigations performed on the homogeneous custom-made Disconti. pipes. In this study, we have expanded our investigations to Diconti. and Conti. manufactured pipes from the regular production. These pipes have shown some differences compared to the homogeneous Disconti. pipes that were used in the earlier investigations. For each set up condition, we had only one pipe in the study, which constitutes a limitation for the repeatability and confirmation of test results. The unaged Diconti. pipes gave us a range of values of the adhesion strength, which creates an uncertainty in comparison with the aged pipes.

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12 Publication list

I. I. Jakubowicz, J.H. Sällström and N. Yarahmadi- Pipeopsy: A Novel Method for Status Assessment of District Heating Pipes in Operation Future Heat report, J. Pipelines syst. Eng. Pract., 2025 16(1)

II. J.H. Sällström, I. Jakubowicz and N. Yarahmadi- Effects of mechanical loads on ageing of prefabricated district heating pipes – Energiforsk report for FutureHeat program July 2025

III. I. Jakubowicz and N. Yarahmadi - Book of Conference- 11th Conference of the Modification, Degradation, Stabilization of Polymers, Palermo 2024

IV. I. Jakubowicz and N. Yarahmadi - Lifetime Prediction Models Based on Accelerated Aging Tests-Euro Heat & Power magazine 11/2025- www.ehp-magazine.com

Appendix

Future Heat report, 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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