IEA DHC|CHP

Annex X Final report

Improved maintenance strategies for district heating pipe-lines

Short title: IMPROVED MAINTENANCE OF DH-PIPES

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Table of Contents

Executive Summary

There are many district heating networks in Europe that are anticipated to be close to their end of life. In order to estimate their remaining technical life, it is crucial to get sufficient information and facts about all parts of the piping systems in advance. The main objective of this project has been to establish facts and tools, which could help us to obtain and predict present and future technical status of pre-insulated bonded district heating pipes in operation. In order to simulate ageing of polyurethane (PUR) insulation an accelerated thermal ageing method was used. Accelerated ageing was performed by applying three different elevated temperatures to the service pipes. The effect of the diffusion of oxygen through the casing was examined by ageing district heating pipes manufactured by Logstor with two different thicknesses of the casing pipes. For investigating naturally ageing, pipes from networks managed by KDHC in Korea and Statkraft in Norway were used.

The project has provided a framework for forecasting future technical status, maintenance needs and energy losses based on knowledge about present technical status, today's maintenance needs and estimated future operating temperatures. Theoretical calculations and information from Korea and Norway DH-pipe networks were used to demonstrate the model.

The evaluation of the technical status of the pipes after artificial or natural ageing was done by measuring the shear strength between the PUR foam and the steel service pipe (adhesion). The tangential shear strength test method was mainly used to evaluate the status of the pipes. The SP plug test method, which is a cheaper and more practical method in the field, was also used, and the results were compared with those from the tangential shear strength test method.

The shear strength was measured for unaged and artificially aged pipes after 4, 8, 14, 18, 27, 36 and 54 weeks of ageing at 130, 140 and 150 ºC in the service pipes and at an elevated ambient temperature 70 ºC. Our results show that the shear strength deterioration of the pipes follows different slopes. The shear strength decreases rapidly in the beginning (the first 8 weeks), then it obtains a stable level, and finally it slightly increases towards the end of our experimental time. The difference between the results of the shear strength for thin and normal casing is not significant. The results of the measured shear strength of the artificially aged pipes after various ageing times and temperatures indicate a similar tendency of deterioration for both tangential shear strength and SP-plug test methods.

For the artificially aged pipes, neither the raising of the ambient temperature from 10 to 70 °C nor the decreasing of the thickness of the casing from 3 mm to 0.13 mm could demonstrate the thermo-oxidative reaction of PUR by speeding up the diffusion rate of oxygen. Results of the shear strength tests for naturally aged supply pipes that are 1-38 years of age show a slow deterioration rate.

In the framework for improved maintenance strategies, loss of adhesion between polyurethane and the service pipe was considered as the failure mechanism. The deterioration of the adhesion was assumed to be a thermo-oxidative process governed by an Arrhenius relationship. In order to show how the development of faults related to adhesion and costs of heat losses in a district heating distribution network, a simplified model of the network in Goyang in Korea was used.

The model was used to forecast the status of the network in the year 2030. The temperature levels in the flow pipe were assumed to increase by 5 °C. This means that the reaction rate will increase by more than 50%. The year, when end of life is reached, was calculated. The number of faults or maintenance actions related to adhesion in the example treated was estimated to increase by a factor of 3.9. The heat losses were estimated to increase by 15%.

Preface

This work is carried out within Annex X (May 2011-April 2014) of 'The IEA Implementing Agreement on District Heating and Cooling including Combined Heat and Power'. This is a collaboration work between the following organisations:

SP Technical Research Institute of Sweden (Contractor)
KDHC - Korea District Heating Corporation (Partner)
Statkraft Varme AS (Partner), and
IMA Materialforschung und Anwendungstechnik GmbH (Partner)

Our partners are represented by Dr Jooyong Kim, Mr Åmund Utne and Mr Jörg Finnberg, respectively. Logstor AS represented by Ms Tina Thomsen has manufactured and delivered pipes for accelerated laboratory ageing experiments, which is gratefully acknowledged.

There has been an expert group consisting of representative form the member states within IEA DHC|CHP. The advice and support are gratefully acknowledged. The expert group consisted of Mr Christian Ting Larsen (Denmark), Mr Veli-Pekka Sirola (Finland), Dr Ingo Weidlich (Germany), Prof Woo Nyon Kim (Korea), Mr Terje Strøm (Norway), Mr Mark Howell (UK) / Dr Robin Wiltshire (UK), Mr Tony Mirabella (US), Mr Thomas Lummi (Sweden).

Göteborg in April

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1 Background

Modernisation of the district heating pipelines is a top priority in order to enhance the efficiency of the distribution systems according to the technology platform DHC+ (2012). In Sweden, approximately 16 000 km of pipeline are installed, with an average construction cost of 500 €/m SDHA (2007). In order for the current replacement rate of 50 km per year to be feasible, an expected technical life of 320 years would be required, while in reality, pre-insulated bonded pipes of current standard may last for 30 – 70 years. These pipes are made up of a steel service pipe, insulating polyurethane (PUR) foam and a protecting casing pipe of polyethylene (PE). This pipe type has dominated the market since the early 80's, and one might therefore expect that the need for replacement may increase by five to ten times the coming years. For Swedish conditions, this means that maintenance of the existing networks will require largely the same investment volume as new construction.

The perspective of this project is widened by taking into account experience of district heating distributers in Korea and Norway. The Korea District Heating Corporation owns about 3 000 km pipeline, which were mostly installed from the early 90's. The installation rate has been about 200 km each year. The Korean net is still immature and only less than 1 km pipeline is replaced each year due to failures. The network in Trondheim in Norway is more mature, and the oldest parts are from the early 80's.

From a strictly technical point of view, status assessment has become a top priority issue during the last years. German field studies have shown that ageing of the polyurethane (PUR) foam does not follow the time/temperature relation on which the EN 253 product standard is based, see the reports by Stadtwerke Leipzig & GEF (2004), IMA & GEF (2006), GEF, IMA & IPF (2011) and the papers by Meigen & Schuricht (2005) and Schuricht (2007). This discrepancy is supposed to be due to oxidative degradation of the foam. The significance of this phenomenon with respect to long term strength and thermal insulation capacity remains to be clarified. In these studies, both new and used pipes have been tested after ageing for learning about the remaining life. Mechanical shear tests and thermal conductivity tests have been carried out in order to evaluate deterioration of the polyurethane due to chemical or physical phenomena. The axial shear strength is a measure of the adhesion of the polyurethane to the service pipe. This adhesion is crucial to maintain, since the temperature induced displacements and stresses in the service pipe are controlled by reactive tractions on the casing pipe by the soil. When the adhesion is lost, fatigue failures of the steel service pipe can occur at bends, branches and valves. In earlier Korean investigations, it has been found that pipes of smaller dimensions deteriorate faster than the larger.

In review of the previous work, it is concluded that it is crucial to map out the complex relationships and understand which degradation process is predominant and under what conditions. The PUR foam thermal and mechanical properties and their deterioration could be affected by changes of solid polymer matrix and gaseous phase derived from a blowing agent. There is still a lack of knowledge on how components of district heating distribution systems alter and deteriorate with time. This makes it difficult to forecast future economy and needs of maintenance and renewal.

The polyurethane foam in pre-insulated pipes can age in different ways as summarized in a literature survey reported by Sällström *et al.* (2012),

- Thermal ageing: At high temperatures the polymer deteriorates, *i.e.*, the polymer structure changes when bonds break. The foam becomes brittle and mechanical properties get worse.
- Oxidative ageing: Oxygen diffuses into the foam through the casing and reacts with the polyurethane oxidatively. The foam becomes brown and mechanical properties get worse.
- Ageing due to cell gas diffusion: The air diffuse into the foam through the casing and carbon dioxide and blowing agent diffuse out of the foam. The thermal conductivity of the foam increases. The solid phase of foam is intact.
- Ageing due to deterioration of polymer structure: At high temperatures (above 150°C) the polymerisation reaction can go in the opposite direction and the polyurethane will be divided into polyol and isocyanate, see the paper by Schuricht & Leuteritz (2010).

1.1 Accelerated thermo-oxidative ageing method

An accelerated ageing method is used for the thermo-oxidation of the PUR insulation in order to speed up the normal ageing process. The activation energy is defined as the minimum amount of energy required to initiate a chemical or physical change. It can be achieved by increasing the temperature using the assumption that the degradation mechanism is described by a simple model given by the Arrhenius equation and the sample is homogeneous and isotropic. Knowing the activation energy E_a, the lifetime at the service temperature can be calculated using the Arrhenius equation as follows and find the operating lifetime:

Equation 1.1

$$t_o = t_e \exp\left[{E_a}/_{R} \left[\frac{1}{T_o} - \frac{1}{T_e} \right] \right]$$

Here, t_o is the calculated lifetime at the operating temperature T_o and t_e is the lifetime at the elevated temperature T_e. It is obvious that the value of E_a and the temperature difference has a crucial role for the calculated operating lifetime. The glass transition temperature is an important parameter for choice of chemical components, see the paper by Hatakeyama *et al*. (2012). The glass transition of PUR can be controlled by changing the polyol part and the reaction conditions, *e.g.*, the chain length of polyols, or the mixing ratio. The polyol part could influence the molecular flexibility at room temperature, which is important for industrial products in order to control the mechanical properties at room temperature. Thirumal *et al*. (2009) have studied the polyols chain extenders and the effect of blowing agent on mechanical properties of PUR.

The value of activation energy seems to be an appropriate parameter for the estimation of the thermal stability and deterioration of the mechanical strength, but our results from the shear strength testing indicate complex and multistep processes. This complexity has also been postulated by Albu *et al.* (2011), when they could not use a simple kinetic analysis strategy due to the different reaction rates. The degradation of PUR could be influenced by separate, simultaneous or synergetic mechanisms. In order to avoid the inefficiency by measuring a polymer's behaviour over a long period of time at a specified temperature, the fact that the polymer will behave the in the same way at higher temperatures and a shorter period of time can be utilized. The deterioration of adhesion is accelerated in time by raising the temperature. Polyurethane is produced by a reaction of an isocyanate with a polyol in the presence of a catalyst. The properties of a polyurethane material are greatly influenced by the types of isocyanates and polyols used.

The labile hydrogen of the urethane is primarily responsible for the colour development in the thermal degradation of the polyurethane. The increase of thermal conductivity is another sign for PUR foam ageing. The ageing effect of closed cell foams occurs, when air diffuses into the foam and the foam gas diffuse out. The air diffusion into the foam is much faster than the foam gas diffusion out of it, see Ostrogorsky *et al*. (1986). Both the type of blowing agent and the cell dimension affect the thermal diffusivity of PUR. In some cases the blowing agent has a big influence on the cell structure and its thermal diffusivity. The foams prepared by use of hydrocarbon mixtures as a blowing agent has shown to have smaller cells with high isotropy in comparison to foams using cyclopentane. Hence, the thermal conductivity of PUR using hydrocarbon mixtures as blowing agent was lower, see the work by Prociak *et al*. (2000). They have shown that the heat transfer process through PUR foam depends not only on the composition of the gas phase within the foam cells but also on the foam cell morphology. Beachell *et al.* (1964) have studied stabilisation of PUR against thermal degradation and shown that the PUR degrades at temperatures in the range 150- 215 °C. In another work Zeid *et al*. (1986) have reported a thermal degradation temperature at 165 °C.

1.2 Future challenges and demands in a larger perspective

The district heating (DH) companies are facing changes in market conditions and technological issues such as decreasing revenues from heat sales due to improved energy performance of the building stock and competition from other energy sources. Furthermore, how to treat third part access is still an open question, when new players with excess heat want to use the existing networks for selling it. The awareness and tools how to handle the future situation in terms of risk management in Swedish DH companies were studied by Lygnerud (2010), who outlined the risks for the DH companies related to direct competition from other energy sources, more demanding customers, unprecedented scrutiny by decision makers and price regulations. Lygnerud means that managing risks in a professional way is a necessary condition for survival of future profitable businesses. A good example of a DH company, which has completed a business analysis in order to survive as a profitable company is Stadsvervarming, Purmerend, in the Netherlands. Van Lier (2010) concluded among other things that the network characteristics have become uncontrollable during the expansions of the network. The energy loss and leakage in the system were estimated with existing means. However, the remaining life of the existing pipes was not determined.

1.3 The need for an improved maintenance strategy of the pipe system

An adequate maintenance strategy that can pinpoint the economically most relevant actions will be instrumental to an economically sustainable network. One key component in such a strategy is to be able to determine the current condition of the pipes in the network. A number of different types of insulated pipes are installed in the existing networks. Pre-insulated bonded pipes with a steel service pipe, PUR-foam and an outer casing of, e g, polyethylene were introduced during the 70s and constitute a gross part of the existing networks. It has been found that this type of pipes may have a faster ageing and thereby a shorter technical life than previously has been stated, see *e.g.*, the paper by Meigen & Schuricht (2005). The ageing implies that the insulation capacity decreases and that the mechanical properties of the PUR-foam changes negatively regarding the ability to sustain external loads and to contribute to the friction fixation of the pipes. Loss of friction fixation (due to loss of adhesion between PUR and service pipe) of the pipes is detrimental to the life due to the increased risk of fatigue in the steel pipe.

A good knowledge of the status of the pipe components in the network implies a number of direct benefits:

- Possibility for the network owner to make correct decisions about maintenance actions and reconstruction
- Possibility to plan maintenance actions (preventive maintenance) which is cheaper than corrective maintenance due to failures.
- Better economic forecasting will be facilitated.
- Possible to optimise the network and the operation.
- The costs for distribution and effectiveness are important at third-party access to the network as clients do not want to be charged for excessive repairs and losses. For the parts signing a transit agreement, it is essential to be able to estimate the value of the transit service depending on the quality and status of the network.

1.4 Related work

In the report from Stadtwerke Leipzig & GEF (2004) and also in the paper by Meigen & Schuricht (2005) results of axial strength of 110 field samples are reported. The axial strength is measured at 23 °C in the laboratory. The samples of naturally aged district heating pipes were taken from flow and return pipes. The samples had been in service for 2-26 years. The axial shear strength was measured to vary from 0.01 to 0.46 MPa. The activation energy 150 kJ/K mole was used for calculating an equivalent service time at the service temperature 120 °C. Comparisons of results with the requirement 0.12 MPa from standard EN 253 and requirement from AGFW of 0.03 MPa were made.

Schuricht (2007) discusses the development of the deterioration of the shear strength. After an initial deterioration rate, the deterioration curve flattens out, which is explained as post curing of the polyurethane foam. After further ageing, the deterioration rate increases again. Samples undergoing accelerated ageing at high temperatures above 180 °C show this behaviour. The importance of the oxidation was also pointed out. In the paper by Schuricht (2007) and in the report from IMA & GEF (2006) the temperature dependence of ageing is evaluated from 78 samples of both flow and return pipes by studying the difference of axial shear strength of flow and return pipe. Deterioration gradients and methods calculating for equivalent time at 120 °C by relations similar to Arrhenius are discussed. Equipment for determining axial shear strength in the field was presented.

GEF, IMA & IPF (2011) reported studies of ageing of polyurethane foam in bottles without and with access to oxygen. The deterioration of the shear strength was investigated. The experiments are carried out in the temperature range from 120 to 180 °C. The activation energy without access to oxygen, *i.e.*, the thermal reaction, was determined to be 98 kJ/mole and the corresponding value with access to oxygen, *i.e.*, the thermo-oxidative reaction, was 190 kJ/mole. Cell gas diffusion and thermal conductivity are also investigated in the report. The deterioration of the axial shear strength is studied for pipes stored at ambient temperature 90 °C and pipes in a test bench with 150 °C inside the service pipe with ambient temperature about 23 °C. In the latter case the temperature of the casing will be about 30 °C. The pipes with 150 °C inside the service pipe show a rapid deterioration, but then the curve flattens out after 5000 h and in some cases the strength even increases. The last results given are for the ageing during 22 000h. There is no rapid deterioration that follows after the flattening out. The deterioration of the pipes stored at 90 °C was less, but they showed a similar behaviour. The continuously produced pipes showed no deterioration for 90 °C. The presence of an aluminium foil or a double thickness of the polyethylene casing gave no essential improvement. Early results of the study are reported in the paper by Schuricht and Leuteritz (2010).

Olsson *et al*. (2001) studied diffusion through the polyethylene casing of district heating pipes. The permeability of carbon dioxide, nitrogen and oxygen was measured. Two experimental methods were used. Further studies of diffusion through the polyethylene casing and also in the polyurethane foam were presented in the paper by Olsson *et al*. (2002). Diffusion of cyclopentane was studied and activation energies for the diffusion of different gases were given. Larsen et al. (2009) concluded that the permeability of carbon dioxide, nitrogen and oxygen is essentially higher for the new bimodal polyethylene than the previously used unimodal polyethylene.

Methods and equipment for measuring oxygen consumption for studying degradation of polymers are review in the paper by Scheirs et al. (1995). Assink *et al*. (2005) investigated oxidation of polyurethane foam with open cells store in air at different temperature levels. The activation energy in the temperature range 50-140 °C was determined to be 87 kJ/mole. The compressive strength showed the same temperature behaviour.

2 Aim

The aim of this project is to give tools and knowledge for better maintenance planning of district heating networks of pre-insulated bonded pipes with polyurethane insulation. The deterioration mechanism studied is coupled to the adhesion between the polyurethane and the service pipe. Knowledge about the deterioration speed is to be gained from accelerated laboratory aged pipes and pipes that have been in field operation. Tools for obtaining technical status of pipes in field operation and in the laboratory are to be developed. The technical status and the deterioration speed will provide ability to forecast future technical status and also remaining technical life of the pipes, when an end-of-life criterion is defined.

The project will also provide a model for forecasting future technical status, maintenance needs and costs and energy losses based on known technical status, today’s maintenance needs and estimated future operating temperatures. Decisions related to actions concerning maintenance, renewal and operational parameter can be based on the results of the model. The developed tools will constitute fundamental parts facilitating monitoring of the condition and managing the risks connected to the distribution network for a district heating (DH) company.

3 Methods for obtaining technical status of pipes

In this project, the focus is technical status of pre-insulated district heating pipes and to provide a better understanding as basic information for forecasting future technical status. The failure mode studied here is simplified and limited to the loss of adhesion between the polyurethane insulation and the steel service pipe. The shear strength of the pre-insulated district heating pipes is a measure of adhesion. There are different measurement methods available that can be used in the laboratory and in the field. Two methods are described in the standard EN 253: the axial shear strength test and the tangential shear strength test. The third method considered is called the SP plug test method, and it has been developed in a previous project.

The axial shear strength is measured by use of a tensile testing machine. Usually three cylindrical pipe samples of length *L* are cut from the pipe. The axial force is applied on the service pipe and the sample rests around the casing pipe, see Figure 3.1.

During each test the maximum axial force F_{ax} is registered and the axial shear strength τ_{ax} is calculated as

Equation 3.1:

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

where

F_{ax} = measured maximum axial force
D_s = outside diameter of service pipe
L = length of test sample

This test can also be carried out in the field, but special equipment is required to apply the axial force to the casing pipe. Radial cuts of the polyurethane and the casing pipes towards the service pipe, which remains intact, have to be sawn. Portions of the casing pipe and the polyurethane on both sides of the sample to be tested have to be removed. The special equipment has to be mounted and fixed to the cleared portion of the service pipe. The axial force is applied and registered, see the report by IMA & GEF (2006).

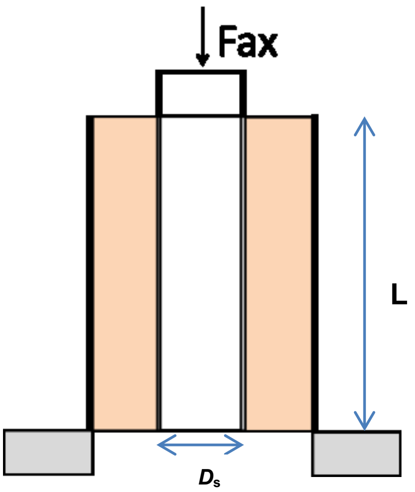

Figure 3.1: Sketch of axial shear strength test method.

Alternatively, a piece of the district heating pipe can be removed and transported to the laboratory and samples are cut for measurements in the tensile testing machine. However, these methods cause large damage to the pipe and in the latter case the pipe has to be taken out of operation.

The tangential shear strength test is carried out on samples of the casing pipe and polyurethane still attached to the service pipe. The samples are cylindrical and formed by radial cuts through the casing pipe and the polyurethane towards the service pipe. The length of the samples is denoted L. No removal of material is required beside the test sample. The test rig consists of two half cylindrical parts fitted with levers, which is mounted on the casing pipe, see Figure 3.2. A rope and pulley system is used for applying the couple. The maximum force F_t is measured and registered.

The maximum couple M_t is given by use of the lever a and the maximum force F_t

Equation 3.2:

$M_t = F_t\, a$

The tangential shear strength is obtained as

Equation 3.3:

$\tau_t = 2\, M_t / \pi\, D_s^2\, L$

where

M_t = measured maximum couple
D_s = outside diameter of service pipe
L = length of test sample

In the laboratory environment the advantages are that many samples can be extracted from one pipe and that the samples can be tested intermittently during artificial ageing without dismounting the pipe. It ought to be possible to build equipment and carry out measurements in the field, but it will be quite complicated.

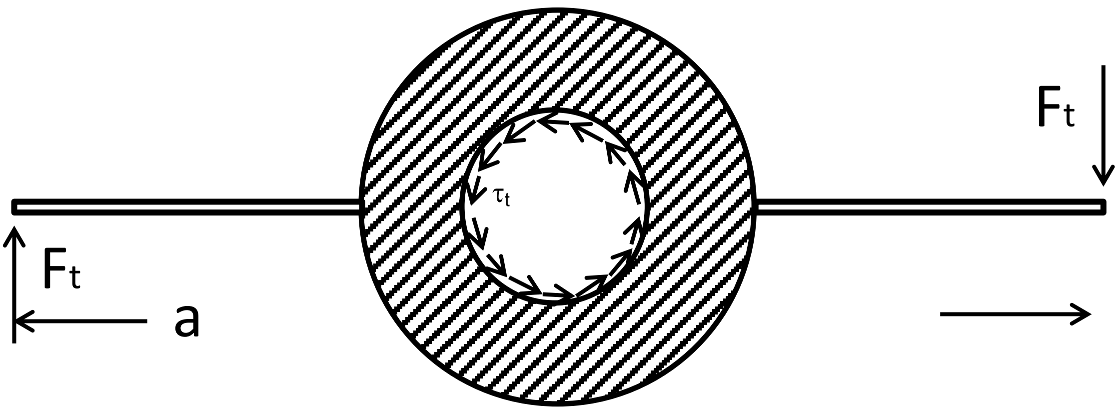

Figure 3.2: Sketch of tangential shear strength test method.

SP plug test method was developed in a previous SP project, see the paper by Sällström *et al*. (2012). A hole saw is used for creating a cylindrical plug attached to the service pipe. Aluminium pipes are glued to the pipe, see Figure 3.3. A rig with a bearing is used for applying a torque manually, which is measured by static torque transducer, see Figure 3.4. The maximum torque M_p is measured and registered.

The plug shear strength τ_p is obtained as

Equation 3.4:

$\tau_p = 16\, M_p / \pi\, d^3$

where

M_p = measured maximum torque
d = diameter of plug

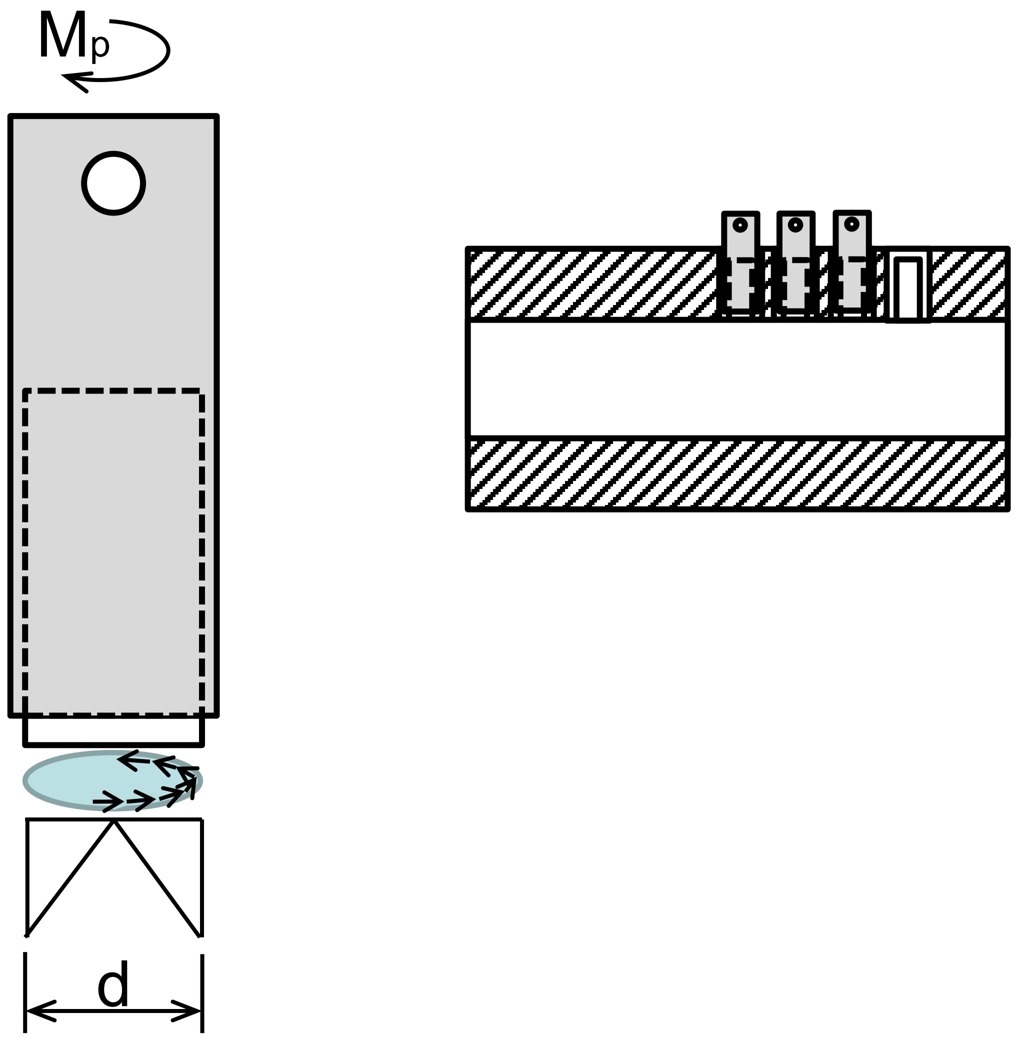

Figure 3.3: Sketch of SP plug test method for measuring shear strength.

In the axial shear strength test method and in the tangential shear strength test method the shear stress will be constant at the imagined fracture surface, but in the SP plug test method the shear stress varies linearly at imagined fracture surface. In the previous study by Sällström *et al.* (2012) a first step towards developing a simple and cheap method for technical status assessments of existing pipes in operation without shutting the pipes down was taken. The advantages are less digging, less damage to the pipe (which can be repaired easily), simple mobile tools can be used for taking samples and performing measurements as compared to field versions of the axial or tangential shear strength test methods. All the presented methods have been used in the project, but the tangential shear strength test method has been most commonly used.

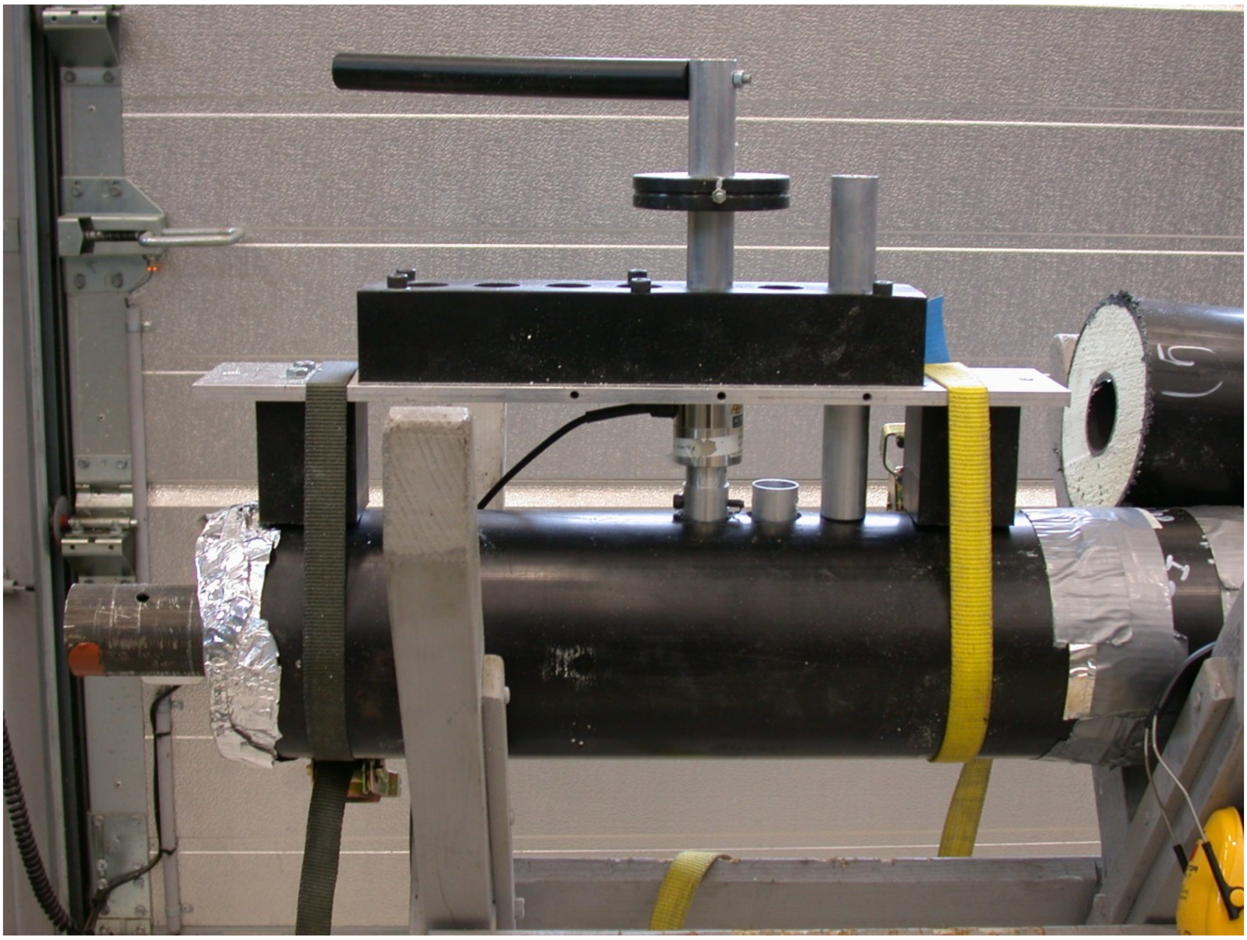

Figure 3.4: Picture of setup of SP plug test method.

4 Definition of technical life

The technical lifetime can be determined based on a standard requirement on the axial shear strength of 0.12 MPa in EN 253, but the pipe will not be subjected to such large shear stresses between the service pipe and the polyurethane foam. Based on the standard EN 13941, the shear stress between service pipe and the polyurethane has been calculated for a few cases; see Table 4.1 and Appendix A. The shear stress is based on the linear built up of the fix force along the friction length. For some extreme cases the shear stress reaches nearly half of the requirement 0.12 MPa. Instead, it is suggested that the definition of lifetime is based on a reduced value that is selected based on the conditions of the particular network.

Table 4.1: Calculation results of shear stress by use of EN 13941. Weight density of soil 18 kN/m^3, lateral soil coefficient 0.5, service pressure 16 bar, Young's modulus 210 GPa, Poisson's ratio 0.3 and thermal expansion 11 10^{-6} K^{-1} of steel have been used.

Dimension	Temper-ature [K]	Friction [-]	Cover [mm]	Shear stress [kPa]
DN 100/225	150	0.6	2000	32
DN 100/225	90	0.6	2000	32
DN 100/225	150	0.4	600	6.9
DN 100/250	150	0.6	2000	36
DN 65/180	150	0.6	2000	39
DN 65/180	150	0.4	600	8.2
DN32/140	150	0.6	2000	54
DN400/710	150	0.6	2000	30

5 Manufactured pipes

Eighteen pipes were manufactured by Logstor with two different thicknesses of casing for this project.Seven pipes DN50/160 of length 6 m with a 3 mm PE casing and 11 pipes DN50/160 of length 6 m with 0.13 mm with PE foil were manufactured. The traditional production method was used, but a mould was used for the pipes with thin casing.

Pipes with 3 mm thick (normal) PE casing were manufactured as follows. First, the distance spacers are placed on the steel service pipe for securing its central position and then the service pipe with spacers is pushed into the PE casing. At last, the end tools with ventilation plugs are mounted on each end and the pipes are prepared for foaming, see Figure 5.1.

According to Logstor the foam material for the pipes contains a Polyol system from Huntsman TE34249 with mixing ratio: pol+cp/Iso = 100+10/183 and output = 1062.5 g/s. The other process parameters: reaction time = cream time 15 s, fibre time 82 s, free rise density = 33 kg/m^3, filling density = 83 kg/m^3 and table slope = 30:600.

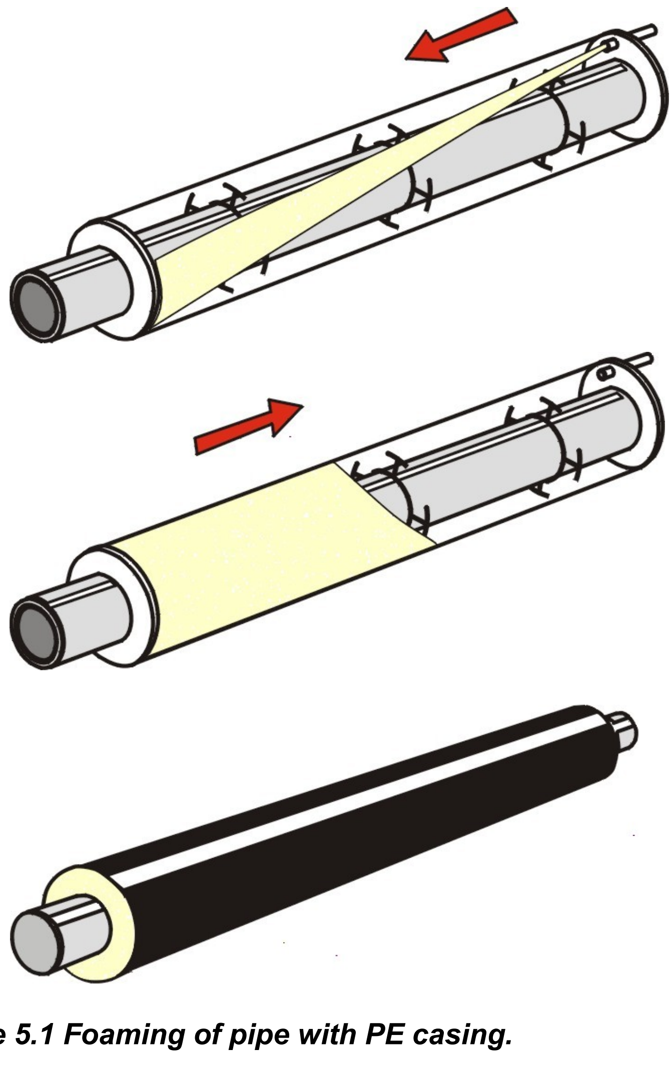

Figure 5.1 Foaming of pipe with PE casing.

The production of pipes with 0.13 mm thick PE foil was described by Logstor as follows. First, the distance spacers are placed on the steel service pipe. Then the steel pipe is pushed into the PE foil. A steel mould is preheated with a gas burner. The steel service pipe and PE foil is placed in the mould. At last, the end tools with ventilation plugs are mounted on each end. The pipe is now ready to be foamed, see Figure 5.2.

Figure 5.2: Manufacturing of pipes DN50/160 with PE foil: Preheating of mould, mould with pipe and manufactured pipes.

6 Artificially aged pipes

The artificially ageing considered was limited to thermo-oxidative process in the polyurethane at the service pipe, *i.e.*, the deterioration of the adhesion between the polyurethane foam and the service pipe. Both HDPE (High Density Polyethylene) casing and PUR insulating foam were exposed to higher temperature than their normal temperatures in operation. A heated chamber was built for creating an elevated ambient temperature. A set up of the new manufactured pipes from LOGSTOR was arranged. The pipes were artificially aged in the heat chamber in order to understand the ageing process, and apply that knowledge on pipes in operation. During the artificial ageing the service pipe were kept at different temperature levels. The reason for using three levels was the intension to calculate the activation energy in the Arrhenius relation. The purpose of the elevated ambient temperature was to increase the diffusion of oxygen through the casing, and hereby the available oxygen for the deterioration of the adhesion at the service pipes. At the same time there will be an accelerated ageing of the polyethylene casing.

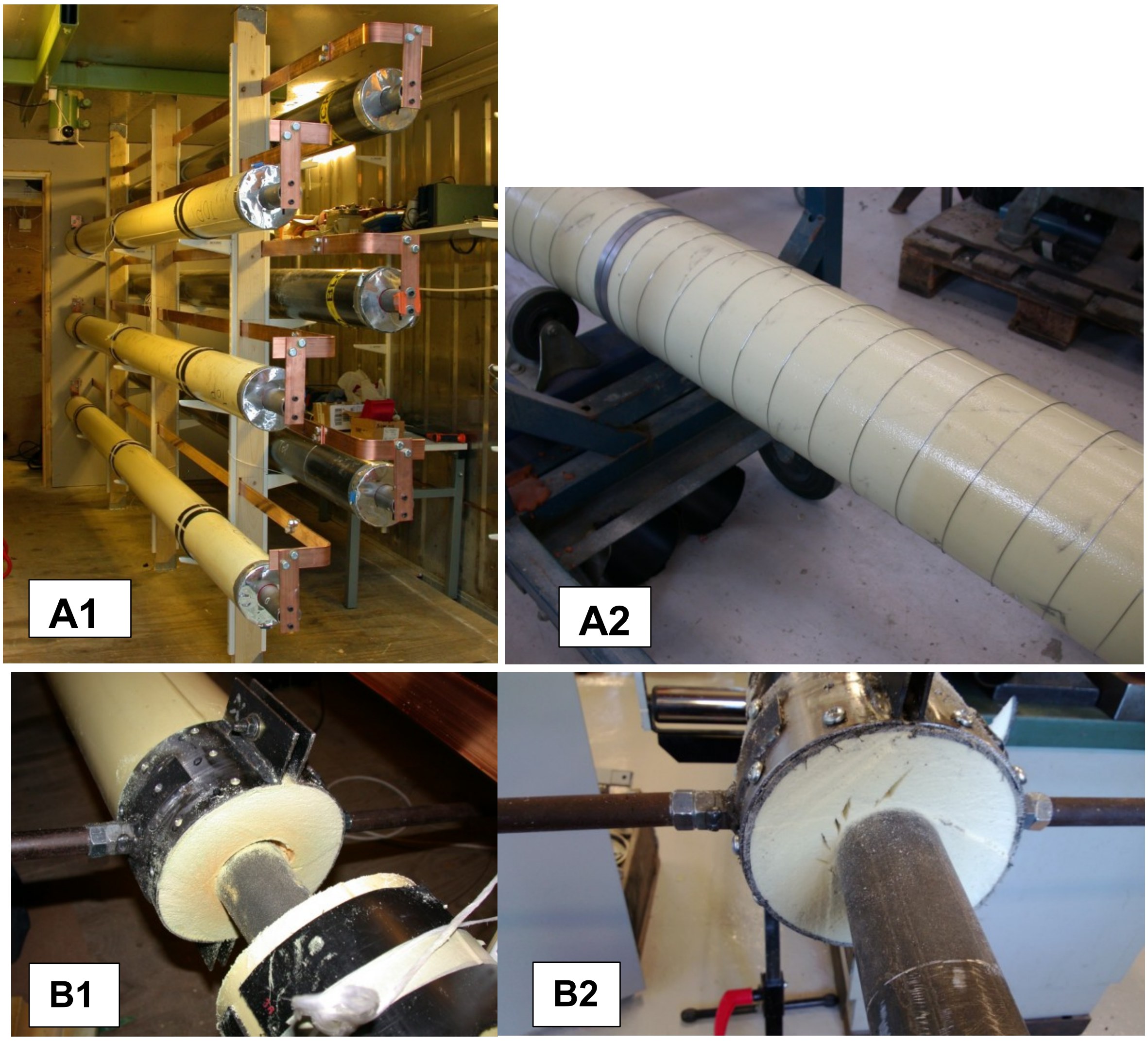

Figure 6.1: A1-artificial ageing set up. A2-pipe with thin casing wounded with steel wire. B1 and B2- Demonstration of tangential shear strength test method.

All pipes had size DN50/160 but two types of casing were used: a traditional casing of thickness 3 mm and a thin casing of 0.13 mm. The thinner casing pipe was chosen for investigating the roll of the oxygen diffusion through the casing by using different barriers against oxygen diffusion. The thin casing means an increase of diffusion rate by 23 times. The pipes were sealed by gluing aluminium sheets at the ends for prohibiting diffusion there. After testing of adhesion the holes in the casing pipes were sealed with aluminium tape.

The pipes were placed horizontally in the chamber with controlled and monitored ambient temperature at 70 °C, see Figure 6.1. The ambient temperature level 70 °C was chosen, since the laboratory equipment could not sustain higher temperatures. In the paper by Olsson *et al.* (2002) diffusion of gases in the PUR foam and through the PE casing is studied. The activation energy E_a for diffusion of oxygen through polyethylene is determined to 35 kJ/mole. The Arrhenius relation gives the quotient of the diffusion rates k_1 and k_2 at the temperature T_1 [K] and T_2 [K], respectively:

Equation 6.1

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

When the temperature in service is assumed to be 10 °C, the elevation to 70 °C, means that the diffusion rate is increased by 13 times according to Equation 6.1. The ideal gas constant is R = 8.314 J/K mole.

The service pipes were kept at four temperature levels: 70°C, 130°C, 140°C and 150 °C. The heating of the service pipes was done by electricity. The experimental set up was completed and artificial ageing of pipes with both a standard and a thinner casing started in November 2012. Measurements of adhesion were carried out on unaged pipes and pipes after ageing for 4, 8, 14, 18, 27, 36 and 54 weeks.

6.1 Experience of elevated temperatures

The raised temperature of the service pipe relative to the ambient temperature is accomplished by leading an electrical current at low voltage through the steel service pipe. The electrical current is applied through copper bars attached at the ends of the service pipe. The copper bars have high thermal conductivity and the convection of heat from these bars and the free steel service pipe caused a temperature gradient along 1 m of the pipe ends. The importance of the temperature gradient was detected during artificial ageing of the district heating pipes. However, it was investigated thoroughly after the artificial ageing of the district heating pipes was completed. The temperature profiles along the pipe at a temperature raise of about 80°C without and with pipe ends insulated with mineral wool are shown in Figure 6.2 and Figure 6.3, respectively. The insulation with mineral wool improved the situation somewhat. Actually to be able to take samples from a longer portion of the pipe additional heating is needed at the ends.

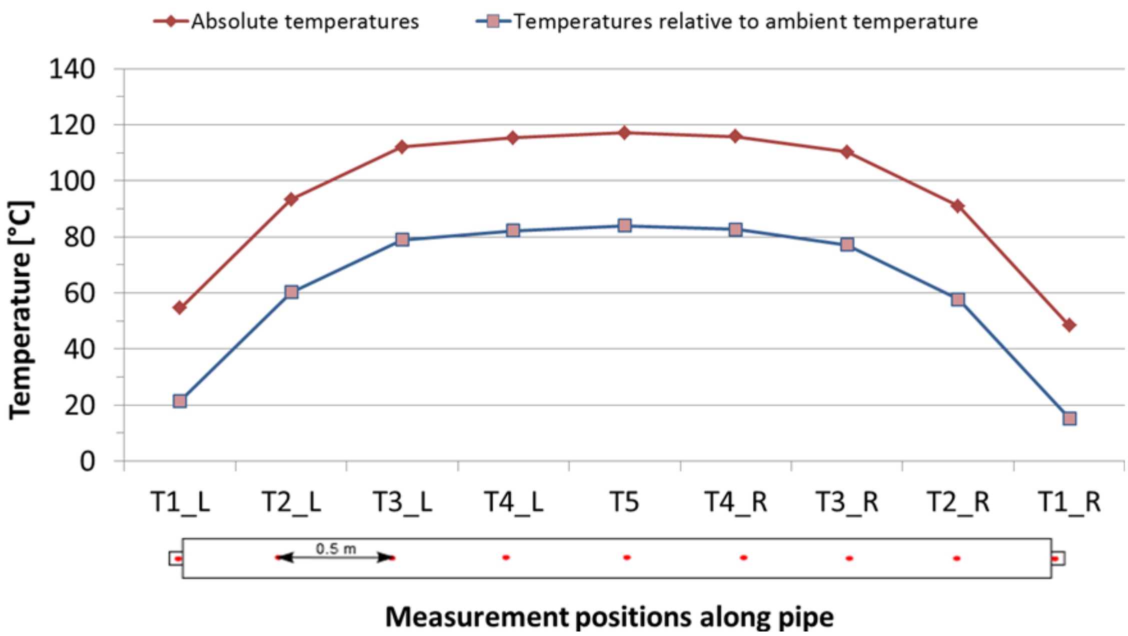

Figure 6.2: Temperature profile in heated pipe without insulated pipe ends, when ambient temperature is 30°C. Temperature raise at location used for control 1 m from pipe end (T3_L) is 79°C, 84°C in centre and 77°C 1 m from opposite end. Temperature raise is 60°C at 500 mm from pipe end.

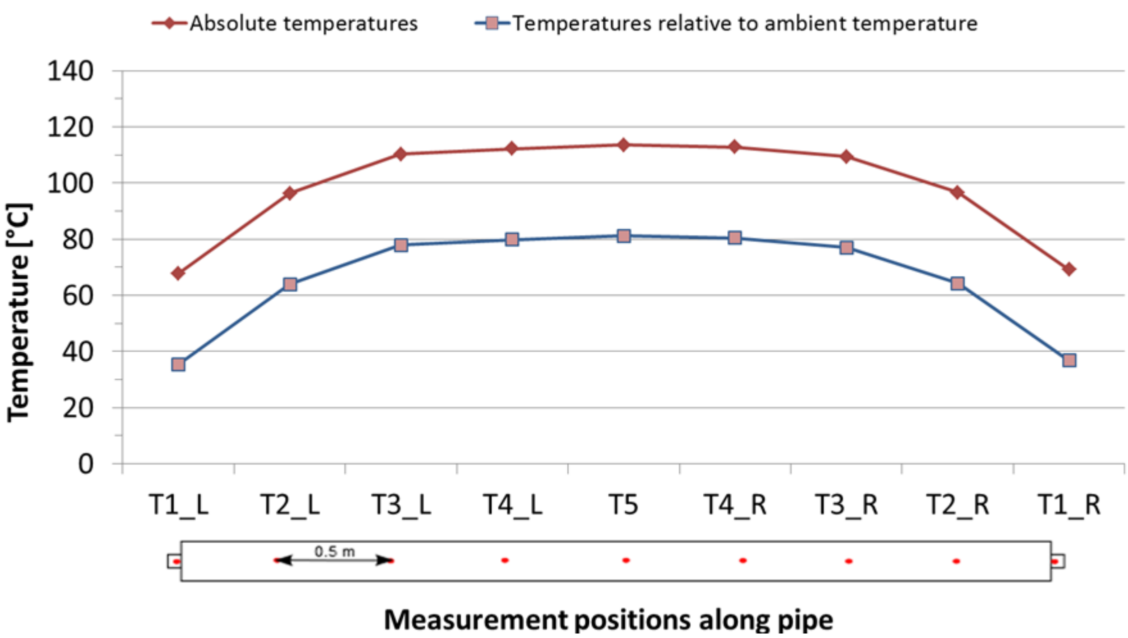

Figure 6.3: Temperature profile in heated pipe with insulated pipe ends, when ambient temperature is 30°C. Temperature raise at location used for control 1 m from pipe end (T3_L) is 78°C, 81°C in centre and 77°C 1 m from opposite end. Temperature raise is 64°C at 500 mm from pipe end.

The intension was to raise the temperatures to 130 °C, 140 °C and 150 °C along more or less the complete pipes. The parts of about 0.3-0.5 m closest to the ends, were not intended for testing due to possible diffusion at the ends in spite of the aluminium barriers, and somewhat decreased temperatures at the ends. Instead of having the possibility to take samples from a length of at least 3 m, there were only 2 m left for testing.

The pipes with raised temperature to 150 °C deteriorated faster than expected. This was considered to depend on that for this specific test set-up a critical temperature was exceeded. Other kinds of faster deterioration reactions might be initiated above 150 °C. For the pipe with the thin casing, the lack of a stiff casing keeping the PUR foam in place, might also influence the deterioration. After ageing 18 weeks the pipes were replaced. The new pipes had insulated ends with mineral wool and the ageing temperature was decreased to 148 °C at 1 m from the end of the pipe.

6.2 Experience with thin casing

After ageing and testing the district heating pipes with the thin casing, it was discovered that the polyurethane had lost the adhesion to the service pipe much faster than expected and as compared to the pipes with the normal casing. In some pipe samples large gaps were found between the service pipe and the polyurethane foam. It was concluded that this might depend on the lack of a stiff casing prohibiting the polyurethane to expand due to the temperature increase. The purpose of the thin casing was to increase the oxygen diffusion throw the casing and into the polyurethane, *i. e.*, to increase the available oxygen at the hot service pipe. In order to compensate for the loss of stiffness of the thick polyethylene casing steel wires were wounded around the thin casing. It was found that a steel wire with diameter 1 mm and spacing 50 mm gives the same stiffness as the polyethylene casing with thickness 3 mm, when Young's moduli for steel and polyethylene are 210 GPa and 1.1 GPa, respectively. The thermal expansion coefficient differs between steel and polyethylene, $12\ 10^{-6}\ K^{-1}$ and $20\ 10^{-6}\ K^{-1}$, respectively. However, the thermal expansion of polyurethane foam is expected to be much larger. Two of the pipes with thin casing 140 °C and 150 °C, were very damaged and replaced after ageing 18 weeks.

7 Evaluation of pipes

Pipe after exposure to accelerated ageing tests in laboratory or natural ageing in the field have been evaluated by using tangential shear strength test method and SP plug test method. The development of the equipment for these test methods has been completed for use in laboratory and heat chamber environment. After each decided accelerated ageing time at least three samples were tested and the results were recorded. In both methods, the results of the shear strength did show similar tendency. For some samples, the shear strength has also been measured with the axial shear strength test method.

The results of measured shear strength of pipes aged during various times and temperatures are presented in Figure 7.1 and Figure 7.2. The tangential and plug test methods were used for pipes with 3 mm PE casing. Each point in diagram is the mean value of at least three measured values.

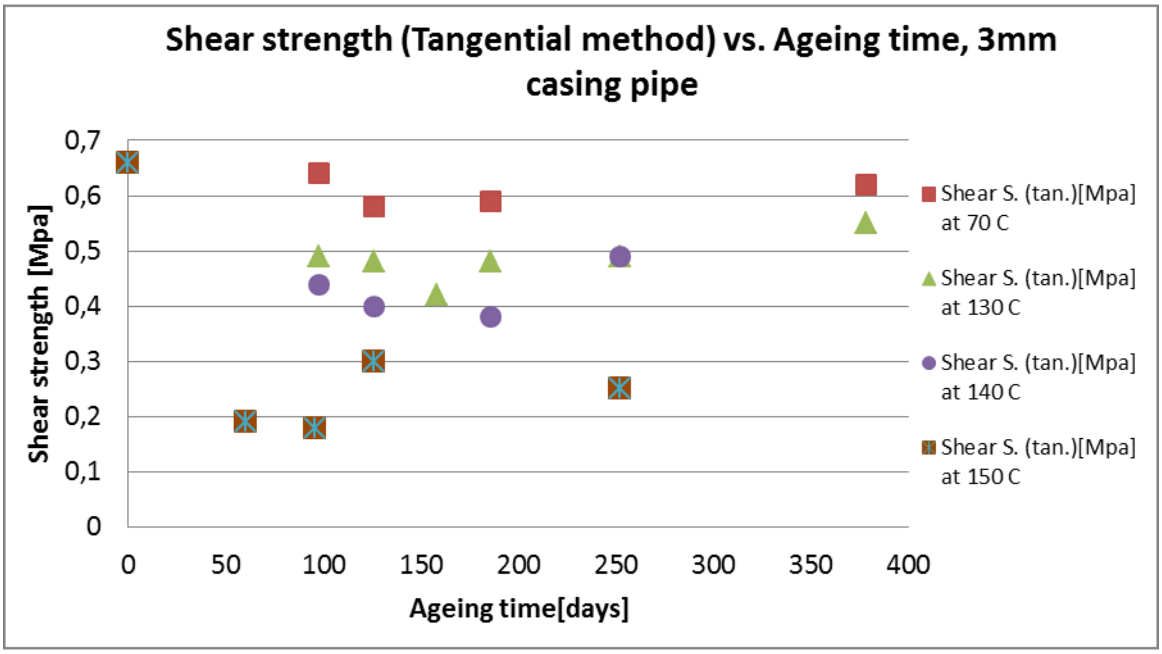

Figure 7.1: Tangential shear strength as function of ageing time for pipes with 3 mm PE casing. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe and ambient temperature is 70 °C.

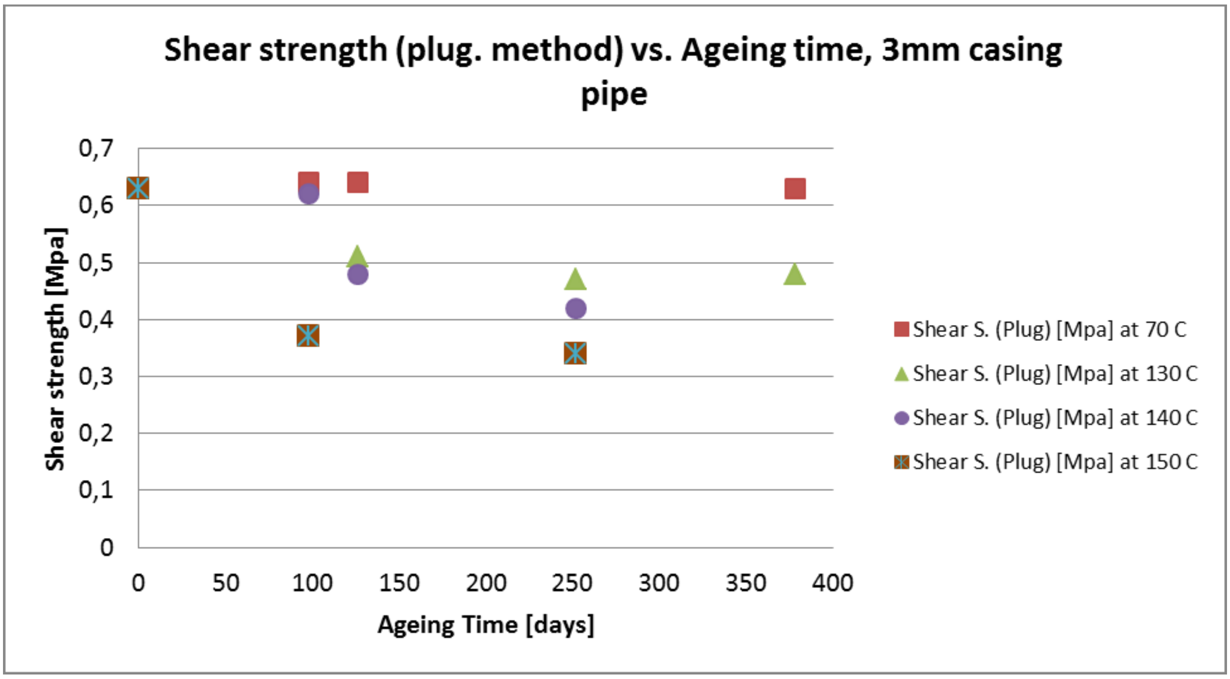

Figure 7.2: Shear strength (plug method) as function of ageing time. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe, while ambient temperature is 70 °C.

Comparisons of the shear strength results from the accelerated aged pipes using tangential shear strength and SP plug test methods indicate generally higher values for the results from SP plug method. However, a similar pattern from both methods for various temperatures have obtained, see Figure 7.3. Higher ageing temperatures for service pipe resulted in higher differences between the results of the tangential shear strength and SP plug test methods.

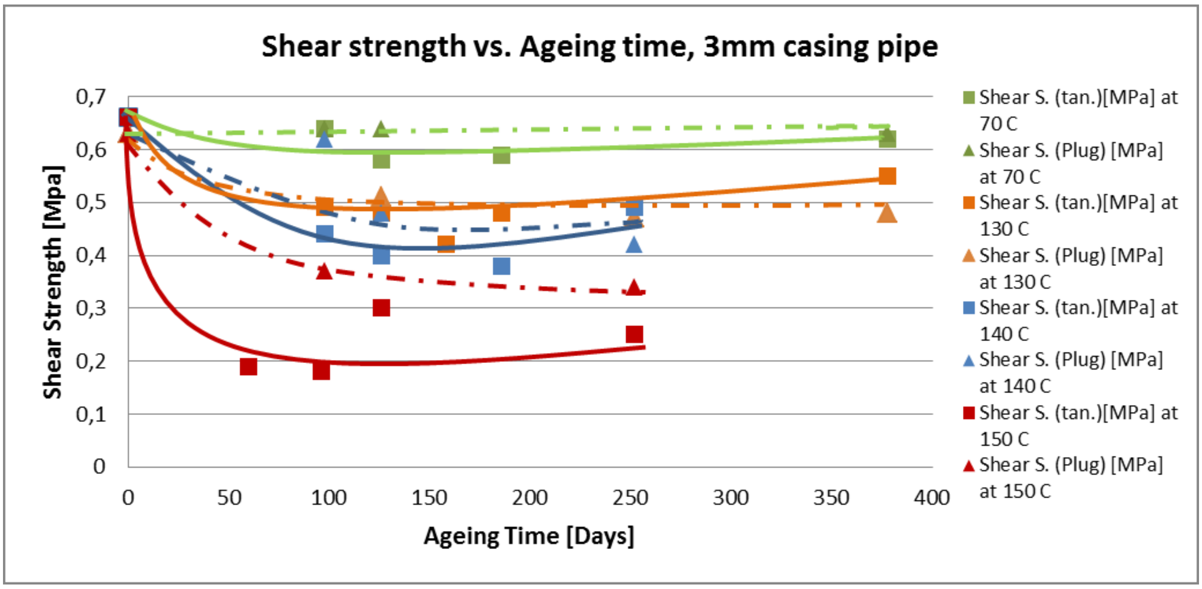

Figure 7.3 Shear strength as function of ageing time measured by tangential shear strength (squares) and SP plug (triangles) methods. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe, while ambient temperature is 70 °C.

The deterioration of the pipes with internal temperature at 140 °C and 150 °C was more severe than anticipated. The results of measured shear strength of pipes aged during various times and temperatures are presented in Figure 7.4 and Figure 7.5. The tangential and plug test methods were used for pipes with 0.13 mm PE casing. Each point in diagram is the mean value of at least three measured values.

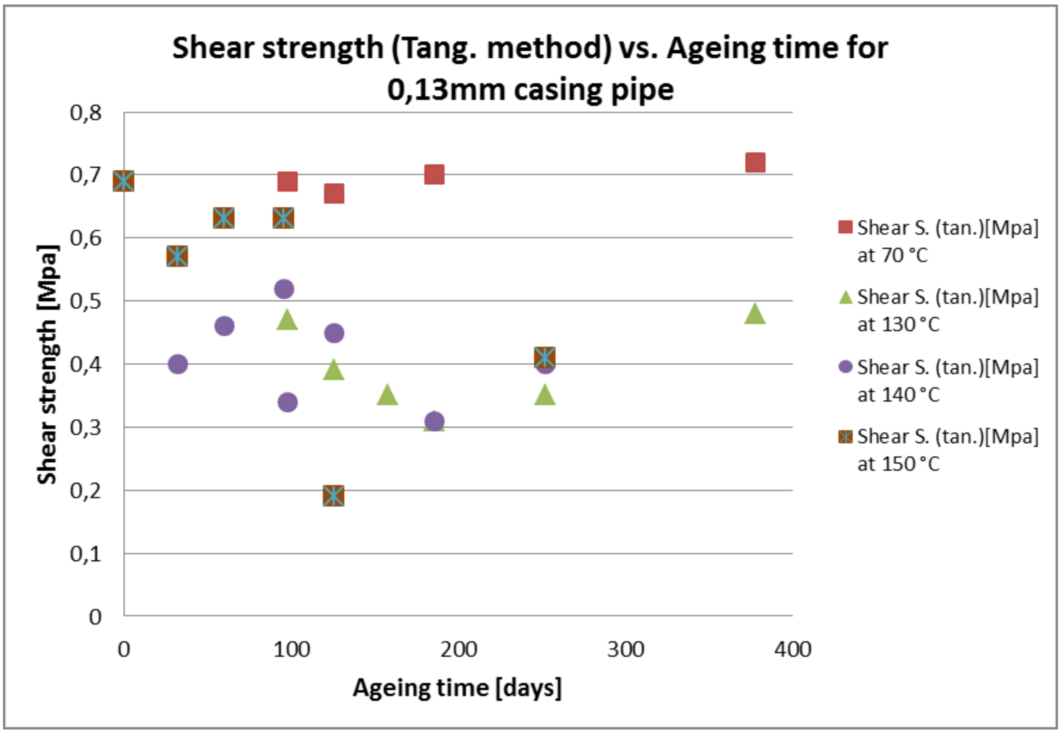

Figure 7.4: Tangential shear strength as function of ageing time for pipes with 0.13 mm PE casing. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe and ambient temperature is 70 °C.

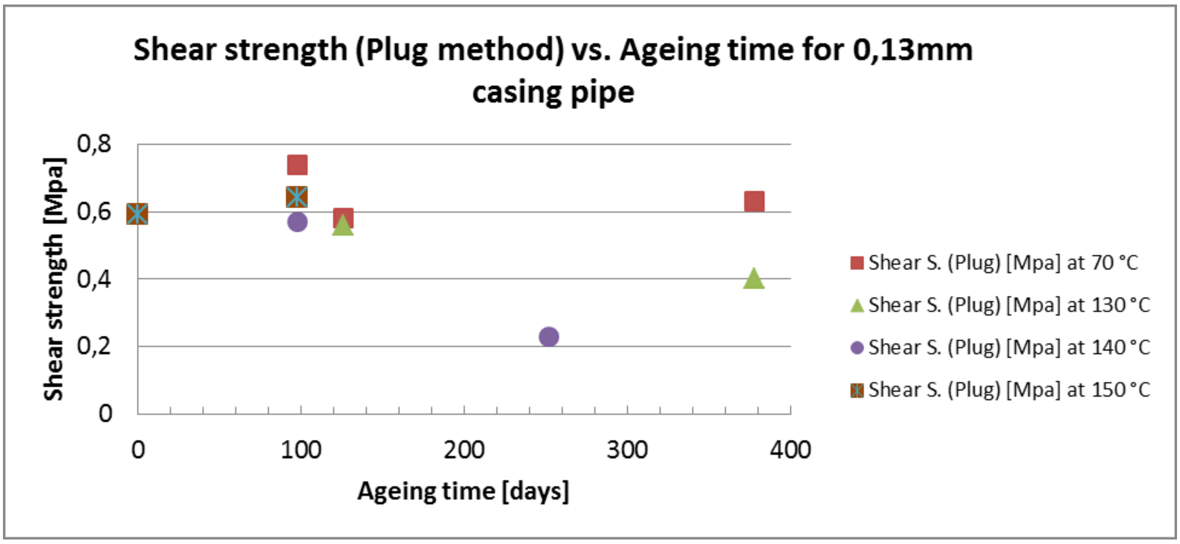

Figure 7.5: Shear strength (plug method) as function of ageing time for pipes with 0.13 mm PE casing. Ageing temperatures are 70, 130, 140 and 150 °C in service pipe and ambient temperature is 70 °C.

The shear strength results of aged pipes using tangential and plug test methods are difficult to compare for the thin casing pipes, since only a few measured samples were carried out with the SP plug test method. The thin casing pipes behaved unexpectedly at high ageing temperatures and the pipes with thin casing aged at 140 °C and 150 °C were replaced after 18 weeks, see the discussion in Section 6.2. Gaps between the service pipes and the PUR foam were observed after ageing of the pipes with the thin casing. The size of the gaps seems to increase by increasing temperature. In Figure 7.6 samples intended for tangential shear strength tests are shown. Both for the pipes with thin and normal casing large gaps have been formed. For the thin casing the gap is larger. The SP plug test samples in Figure 7.7 display cohesion fractures for unaged pipes and a combination of adhesion and cohesion fracture for the aged pipes. For the latter case, the initial fracture is probably due to adhesion failure.

Figure 7.6: Picture of samples after tangential shear strength tests after ageing 14 weeks at ambient temperature 70 °C and at service pipe 150 °C. Gaps have been formed around service pie. Left: Pipe with thin casing 0.13 mm. Right: Pipe with normal casing 3.0 mm.

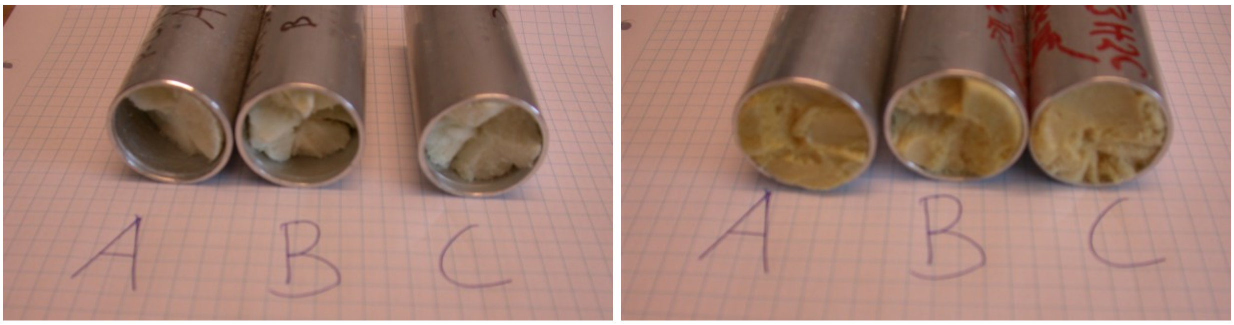

Figure 7.7: Picture of samples after SP plug tests for pipe with normal casing 3.0 mm. Left: Unaged samples. Right: Samples of pipes ages 14 weeks at ambient temperature 70 °C and at service pipe 150 °C .

In Figure 7.8 an attempt to find a tendency curve for the obtained results from accelerated ageing pipes is made. The purpose is to clarify the behaviour of deterioration of shear strength. The slope of the tendency curves for 130 °C, 140 °C and 150 °C ageing temperatures show that the shear strength decreases rapidly during the first period of time less than hundred days and then it flattens out. After about 200 days the tendency lines show another slope with slightly increasing shear strength. Similar observations are also discussed by Schuricht (2005) for pipes aged at high temperatures in the laboratory, but after long time the ageing plateau was followed by a faster deterioration of strength. Linear regression curves are shown in Appendix B and confidence intervals for deterioration rates are given. In three of four cases the confidence intervals given contain zero slopes. This means that the continuous deterioration rate cannot be concluded.

A possible explanation of the initial deterioration could be the increase of the cell pressure and volume due to increased temperature in the cells adjacent to the service pipe according to equation 7.1.

Equation 7.1

$$PV = nRT$$

Here, the variables are pressure *P*, volume *V*, amount of gas *n*, the ideal gas constant *R* and temperature *T*. In this situation, there will be large stresses and strains in cell walls attached to the service pipe. There will also be stresses, due to that the thermal expansion for PUR is higher than for steel. The adhesion between PUR foam and service pipe will successively decrease when cell walls break. This could explain why the decrease in the shear strength is more pronounced at higher temperatures and also why the strength flattens out with time, when a new stable configuration is reached. This hypothesis is also strengthened by the observation of the formation of gaps between the service pipes and the PUR foam for the thin casing pipes aged at 140 °C and 150 °C.

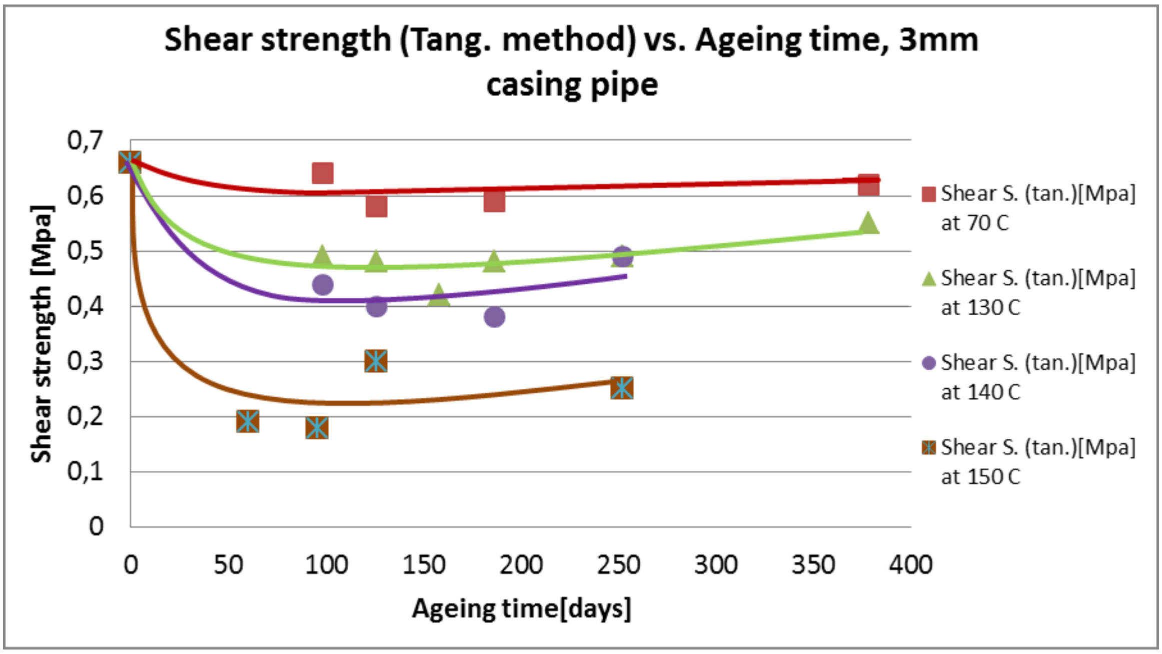

Figure 7.8: Tangential shear strength vs ageing time for pipes with 3 mm PE casing.

The purpose of ageing of the thin casing pipes at the elevated ambient temperature was to speed up the diffusion rate of oxygen and to demonstrate if the thermo-oxidative reaction of PUR is liable for the degradation process. Both decreasing of the thickness of the casing from 3 mm to 0.13 mm and raising the ambient temperature from 10 to 70 °C were applied for increasing the diffusion rate of oxygen through the casing.

Figure 7.9 shows a comparison of the results for the shear strength *vs*. ageing time for the pipes with 3 mm and 0.13 mm casing aged at 130 °C in service pipe, which is not so far from operation temperature of a supply pipe. The difference between the results of the shear strength for thin and normal casing is insignificant. The results show, that the decreasing of the shear strength flattens out after a while and does not change upon prolong exposure. It means that the decreasing of the thickness of the casing and the following increased diffusion rate of oxygen have not shown any effect on the shear strength. Furthermore, if the PUR degradation is dominated by thermo-oxidation, the degradation process should continue to complete loss of mechanical strength and should not level out as was the case in our experiments.

Consequently, our results from the accelerated ageing tests, as presented in the graphs in Figure 7.9 show that the changes of the shear strength do not depend on the thermo-oxidation of PUR, since the degradation processes of the two casings have not significantly different slopes and they do not continue to zero. Instead, the processes seem to have a physical character. There is a need for further studies of the insulation material and the morphology of it in the pipe systems, and the various processes linked to the different slopes of the shear strength change.

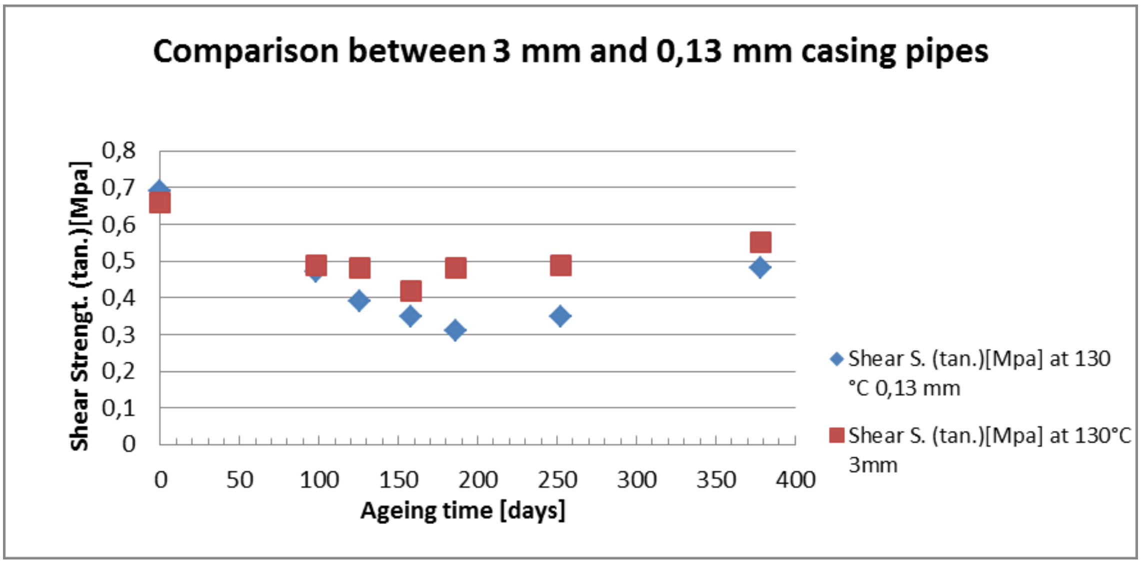

Figure 7.9: Comparison of tangential shear strength as function of ageing time for pipes with 3 mm and 0.13 mm PE casing at 130 °C.

8 Case study of pipes in operation

In order to try to understand the natural ageing process for DH pipes and correlated that to the laboratory study with accelerated ageing of pipes, a case study has been performed. Old pipes from operation for the case study were selected from two different DH networks and delivered to SP: the district of Goyang in Korea and Trondheim in Norway owned by KDHC and Statkraft, respectively. All pipes were in operation until 2013 and dug out 2013. The pipes had been installed at different points in time and aged between one and 38 years. Results from previous German studies are also discussed in this chapter.

The dimension, place, age, installation time, supply and return temperatures of pipes in operation are summarised in Table 8.1. A pipe sample is shown in Figure 8.1. Some of these pipes were measured by using both the tangential shear strength test method and the SP plug test method. Our equipment for testing of tangential shear strength was built for, and limited to, the casing diameters 150 and 200 mm. The pipes with other casing diameters were only tested with the SP plug test method. The axial shear strength was also tested for a few pipes.

Table 8.1: Data of naturally aged pipes from Norway and Korea.

Dimen-sion *DN*, Length [m]	Casing dia-meter [mm]	Test method	Place	Time in opera-tion [years]	Installa tion year	Supply tempera ture [°C]	Return tempera ture [°C]
250, 0.5	405	Plug	Gamle Okstadbakken, Norway	27	1986	120	80
80, 1.5	165	Plug, axial	Middelfarts veg, Norway	5	2008	120	80
150, 1.5	255	Plug	Lade østkurs, Norway	1	2012	110	75
100, 2.0	205	Plug, tangential	Tunga, Norway	38	1975	110	75
150, 2.0	250	Plug	Ladetorget, Norway	14	1999	110	75
50, 3.0	130	Plug, axial	M. Lagabøters vei, Norway	16	1997	110	75
100, 3.0	200	Plug, axial, tangential	Goyang, Korea	18	1995	115-120	55
125, 3.0	225	Plug	Goyang, Korea	18	1995	115-120	55

Figure 8.1: Supply pipe from Goyang network in Korea after 18 years in operation

It is important to emphasize the significant differences between pipes, that have been used in real-life operation and those manufactured for our laboratory testing. The recipes of the materials used and the manufacturing procedures of the HD-pipes have been changed due to development and regulations. There are differences concerning the PUR and its morphology, the blowing agent and the HDPE and its thickness. The pipes from Goyang in Korea had the blowing agent CFC 11 and the casing HDPE pipes were 3.5 mm thick.

The shear strength of supply and return pipes in operation are presented in Figure 8.2 and Figure 8.3, respectively. The oldest pipe (38 years) and the youngest pipe (one year) from Norway have been exposed to the same temperatures for the supply and the return pipes, respectively. When looking at the shear strength results measured by SP plug test method on the supply pipes in operation, irrespectively of the type of polyurethane and blowing agent used, a slow degradation rate is shown during 38 year of service for the Norwegian pipes, see Figure 8.2. A slow degradation is also indicated by the axial shear strength results (see dashed lines).

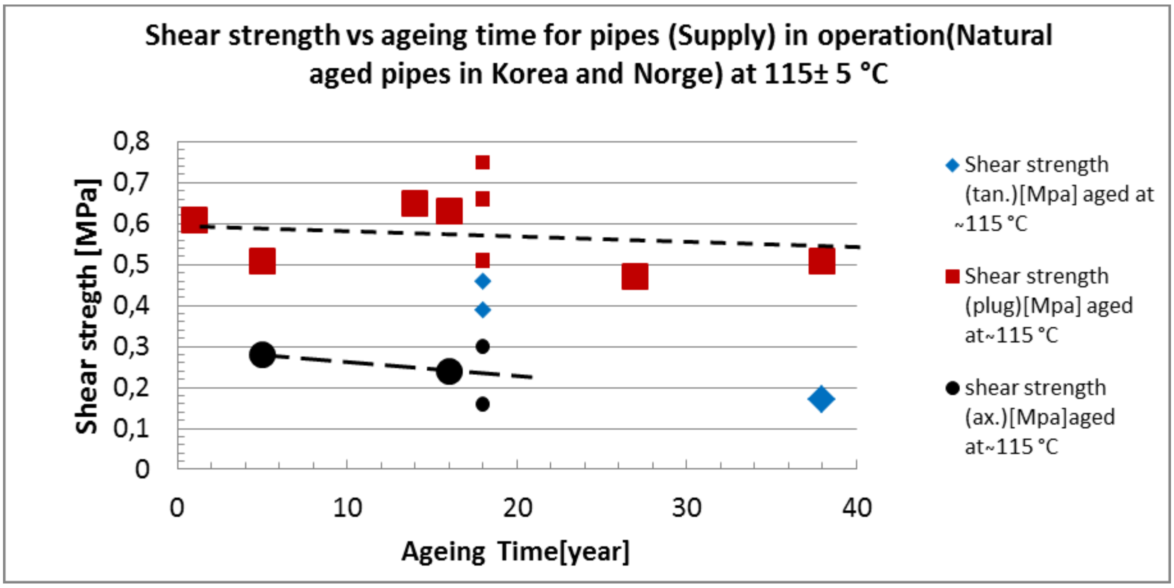

Figure 8.2: Shear strength as function of ageing time for supply pipes aged naturally in operation from Norway and Korea. Results signed by squares come from plug tests of pipes. Diamonds indicate results from tangential strength tests. Circles indicate results from axial shear strength tests. Small and large marks indicate results of pipes from Korea and Norway, respectively.

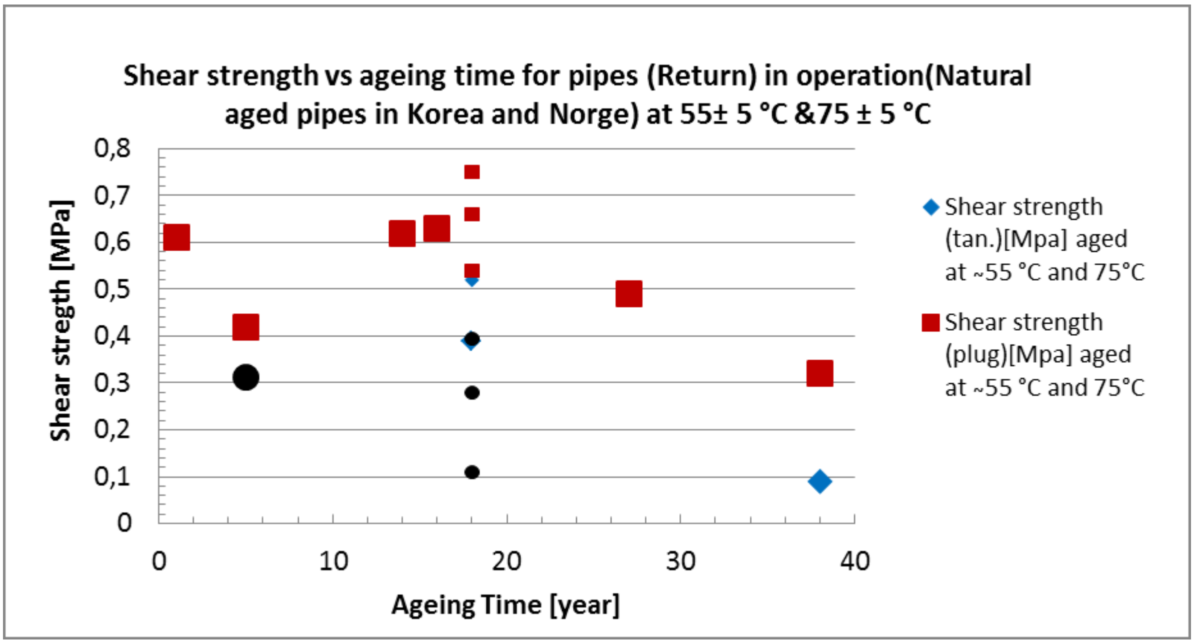

Figure 8.3: Shear strength as function of ageing time for return pipes aged naturally in operation from Norway and Korea. Results signed by squares come from plug tests of pipes. Diamonds indicate results from tangential strength tests. Circles indicate results from axial shear strength tests. Small and large marks indicate results of pipes from Korea and Norway, respectively.

Results from some relevant works previously presented in reports by Stadtwerke Leipzig & GEF (2004) and IMA & GEF (2006) have been summarized by IMA in tabular format and sent to SP. The results of axial shear strength measured in the field on pipes in operation are presented in Figure 8.4 and Figure 8.5. When testing at a higher temperature level than 23 °C, the shear strength could become lower than at 23 °C. The mean of the shear strength for the supply pipes lie at 0.16 MPa and for the return pipes at 0.24 MPa.

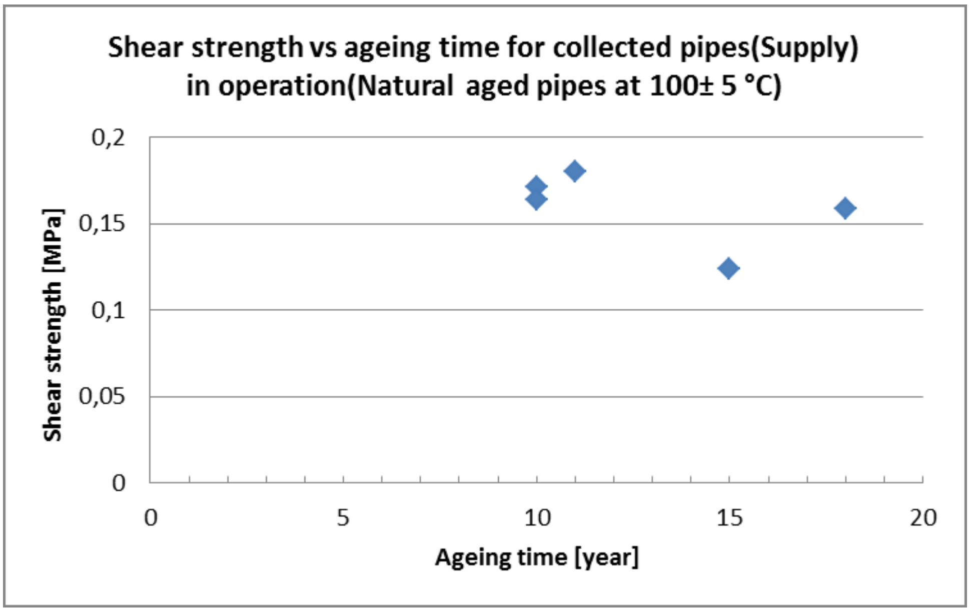

Figure 8.4: Axial shear strength of German supply pipes measured on site at operation temperature.

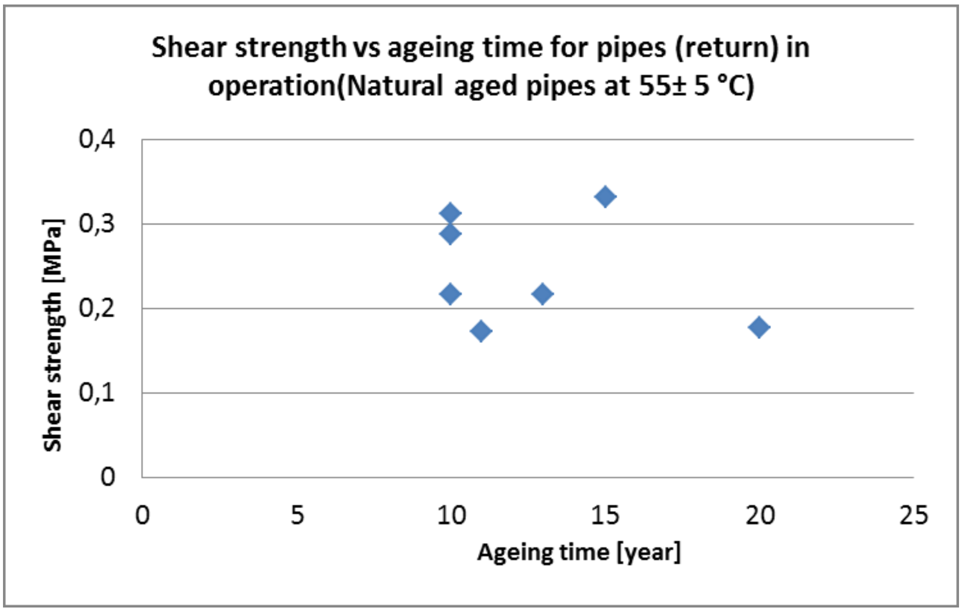

Figure 8.5: Axial shear strength of German return pipes measured on site at operation temperature.

In order to investigate the variation of the results obtained with SP plug test method, samples have been taken equidistantly around the circumference of the casing, see Table 8.2. The relative standard deviation is calculated as the quotient between the standard deviation and the mean value. The relative standard deviation is in average about 0.20 for the samples taken around the circumference. In a few cases it is as high as 0.40. For the laboratory aged pipes, the same tendency of the measurement results of the SP plug test method was obtained as for the tangential shear test method. In Figure 8.6, the measurement results for the same pipe and the ageing time obtained by use of the tangential shear strength test method and the SP plug test method are plotted against each other. Each measurement result is a mean value of three measurements. The correlation between the results from the two methods is 0.74.

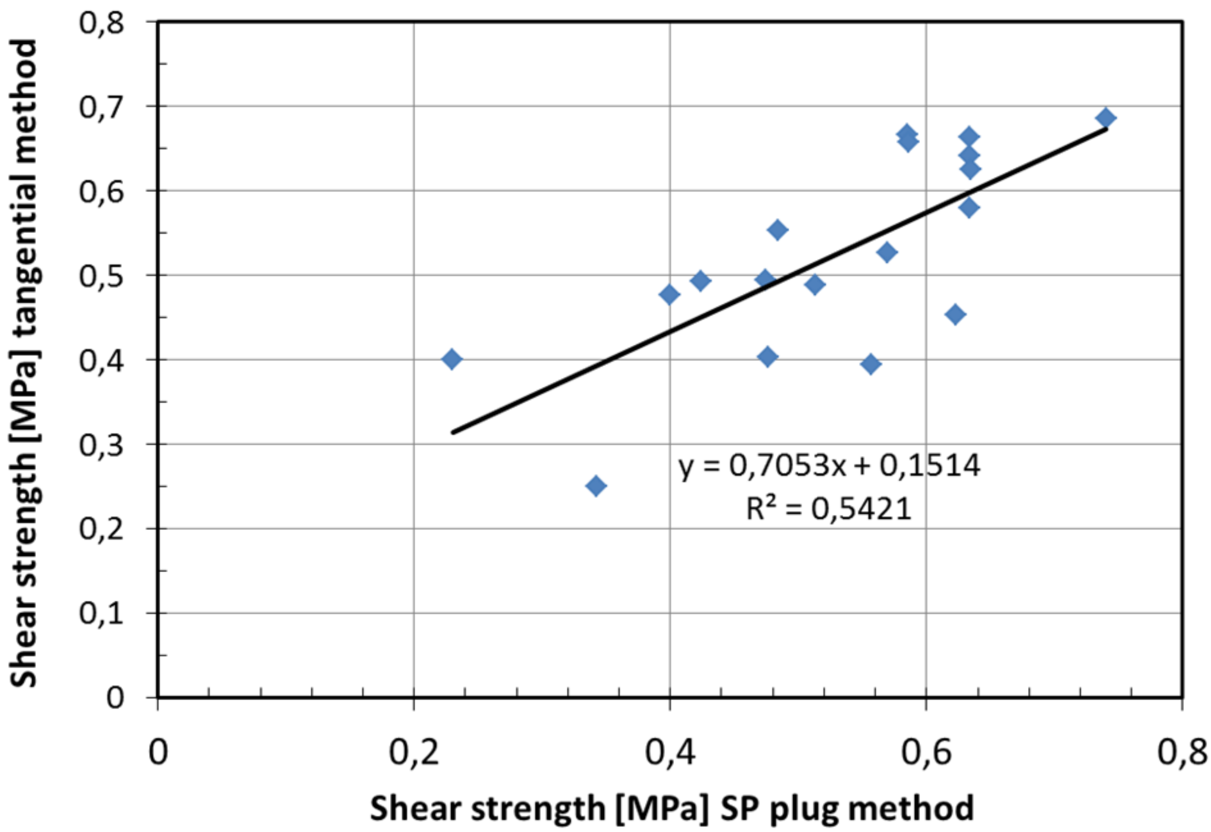

Figure 8.6: Correlation of shear strength measured with tangential shear strength method and SP plug test method.

Table 8.2: Results of SP plug test method for pipes from operation in Norway and Korea. Samples are taken at three equidistant positions on circle around casing, except for large pipe with casing 405 mm. For that pipe, samples are along one generatrix.

Specification				Shear strength for test			Shear strength		
DN	Casing [mm]	Place	Return/ Supply	1	2	3	Mean	Standard deviation	Relative standard deviation
250	405	Gamle Okstadbakken, Norway	Return	0.50	0.43	0.55	0.49	0.06	0.12
			Supply	0.48	0.48	0.45	0.47	0.02	0.04
80	165	Middelfarts veg, Norway	Return	0.59	0.27	0.39	0.42	0.16	0.38
			Supply	0.57	0.45		0.51	0.09	0.17
150	255	Lade østkurs, Norway	Return	0.52	0.65	0.66	0.61	0.08	0.13
			Supply	0.71	0.58	0.53	0.61	0.10	0.16
100	205	Tunga, Norway	Return	0.28	0.45	0.24	0.32	0.11	0.35
			Supply	0.74	0.49	0.30	0.51	0.22	0.43
150	250	Ladetorget, Norway	Return	0.63	0.58	0.58	0.60	0.03	0.05
			Supply	0.74	0.71	0.49	0.64	0.14	0.21
50	130	M. Lagabøters vei, Norway	Return	0.68	0.68	0.53	0.63	0.09	0.14
			Supply	0.61	0.73	0.55	0.63	0.09	0.14
100	200	Goyang, Korea	Return	0.76	0.52	0.70	0.66	0.12	0.19
			Supply	0.77	0.55	0.65	0.66	0.11	0.17
100	200	Goyang, Korea	Return	0.61	0.61	0.41	0.54	0.12	0.21
			Supply	0.47	0.45	0.59	0.51	0.08	0.15
125	225	Goyang, Korea	Return	0.65	0.87	0.73	0.75	0.11	0.14
			Supply	0.68	0.85	0.71	0.75	0.09	0.12

9 Correlating results from artificially aged pipes with case studies

The purpose of this part was to find a correlation between the ageing process in the pipes aged in laboratory and the naturally aged pipes in operation, when it is presupposed that the ageing mechanism is the same. It is also assumed that the deterioration caused by ageing could be reflected by the shear strength of the pipes. However, our study has shown that the shear strength deterioration of the pipes follows different rates, when it rapidly decreases at the beginning and then obtains a stable level (the curve flattens out), and after that slightly increases towards the end of our experimental time, see Figure 7.8. The results have not shown any corroborating evidence for Arrhenius relationship in support of the calculation of the activation energy. Similar results have also been achieved from shear strength tests of the supply pipes in operation after various service times. The original values of the shear strength of these pipes are not available. Hence, it is difficult to say how much they have changed during the operation time. Regardless of variation of type of pipes and the original values of the shear strength, the results have shown almost the same level of the measured shear strength, see Figure 8.2.

In Figure 9.1, the stable level values of the shear strength at various ageing temperatures (see Figures 7.8 and 8.2) are plotted against the temperatures. It is clear that the stable level value of the shear strength decreases almost linearly with increasing temperature, but it is not directly dependent on the ageing time within our investigated time limit. It is also shown that the values from the naturally aged pipes fit very well into the set of values from the accelerated laboratory ageing. These results represent the strong indication that the ageing process is of a physical nature and not a result of an oxidation process.

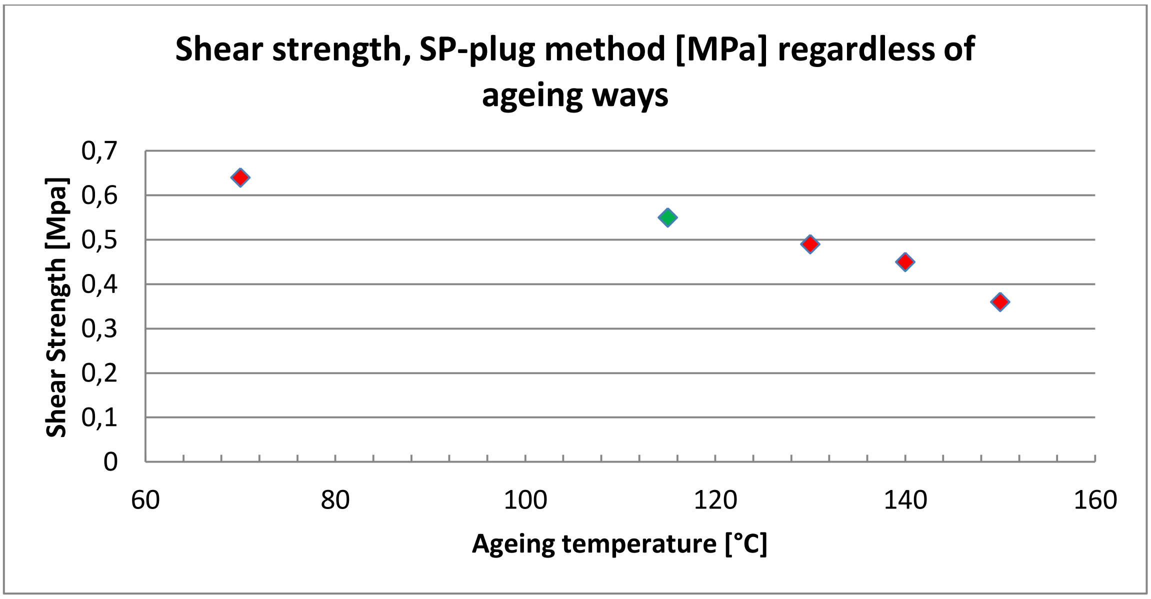

Figure 9.1: Shear strength versus temperature of pipes regardless of type of ageing. Green point represents stable level of naturally aged supply pipe and red points represent stable level of accelerated ageing pipes.

The stable level values of the flatten part of the shear strength curve for the artificially aged pipes and the pipe from operation versus temperature are also presented in Table 9.1.

Table 9.1: Input data to Figure 9.1.

Stable level of shear strength [MPa]	Ageing temperature [ºC]	Operation temperature of supply pipe [ºC]
0.64	70	
0.55		115
0.49	130	
0.45	140	
0.36	150	

10 Model for improved maintenance strategies

Maintenance cannot be considered as a separate action that can be optimised within any company. In the short run the profit of the company can be optimized by neglecting the maintenance, but after some years problems with malfunction systems will eventually occur. There will be costs for repairs and also for loss of sales. There can also be fines related to lack of delivery. The other extreme would be maximize the status of the asset at any costs, and try to keep it as new.

Instead, the life cycle of the asset has to be considered. The asset has to be acquired, utilized, maintained and eventually disposed. During the life cycle of the asset the costs, the risks and the performance of the asset shall be optimized. Here, the asset is the heat district distribution system and we focus on companies managing these systems. However, in this project not all type of maintenance activities related to the distribution system is considered. Here, we focus on the adhesion between the polyurethane and the service pipe.

Hence, the failure mechanism is considered as loss of adhesion between polyurethane and the service pipe. Let us assume that we start out with a stress free district heating distribution system. When the temperature within the district heating system increases, the steel service pipe will expand. When there is adhesion between the polyurethane and service pipe and also at the casing pipe, the soil will induce friction forces along the casing. In the zones near bends where the pipes move, the axial force is built up to the fix force where axial strain becomes zero. The soil and the adhesion limit the displacements due to temperature changes in the district heating system. This also means that bending stresses at bends and T-pieces will also be limited. When adhesion is lost, fatigue of the steel service pipe at bends and T-pieces occurs due to the variation of distribution temperature. In the standard EN 253 it is stated that the adhesion or axial shear strength should be more than 0.12 MPa. This limit can be used for judge the status of the district heating pipe. A lower value can also be chosen, but the risk of failures can then increase above an acceptable level.

Besides the failure mechanism and the acceptable limit a status assessment method is needed. Field measurements methods, like the SP plug method can be used as a tool to measure the adhesion value. If no up to date measurements are available, estimations can be obtained from, e.g., previous measurements and deterioration functions.

The deterioration of the adhesion is in this chapter assumed to be a thermo-oxidative process governed by an Arrhenius relationship. The hypothesis of a physical deterioration mechanism is not yet proven and therefore not used here. The reaction rate k_1 at the temperature T_1 [K] depends on the activation energy E_a as

Equation 10.1

$$k_1 = A_0 \exp\left[-\frac{E_a}{RT_1}\right]$$

The ideal gas constant is denoted R. The deterioration function can be used to estimate the actual status of the adhesion today from previous measurements and also give prognoses of future status, based on the choice of operating temperature.

In order to plan the maintenance or the renewal pertaining to the loss of adhesion. The status of the flow and return pipes have to be known after a certain service time t_a. For constant reaction rate, the status of the flow and return can be written,

Equations 10.2 a,b

$$s_f = s_0 - k_f t_a$$

$$s_r = s_0 - k_r t_a$$

The initial adhesion s_0 is assumed to be the same for the flow and return pipes. For the flow and return pipes, the reaction rates are

Equations 10.3 a,b

$$k_f = A_0 \exp\left[-\frac{E_a}{RT_f}\right]$$

$$k_r = A_0 \exp\left[-\frac{E_a}{RT_r}\right]$$

The operating temperature in the flow pipes is denoted T_f and the return temperature T_r. The initial status is obtained as

Equation 10.4

$$s_0 = \left[\frac{k_f}{k_r} s_r - s_f\right] / \left[\frac{k_f}{k_r} - 1\right]$$

By use of Equations 10.2 a,b, Equations 10.3 a,b and Equation 10.4 the status of the particular pair of pipes can be predicted for a future point of time t_b. During a certain degradation period studied, the operating temperature can vary with the season which can be taken into account by applying a method of lumping the time for a set of temperature spans. Say that three temperature levels are used, which give three degradations rates. A sum for this can be introduced in Equations 10.2 a,b with products of degradation rates times the pertaining operation times.

To be able to predict future maintenance related to adhesion, the maintenance pertaining to failure of adhesion has to be known at a certain time. For the time the maintenance is known the strength can be estimated from previous measurements. A simpler scenario would be to have measurements of strength and required maintenance for the same point in time. In the model it is assumed that the maintenance will increase in proportion to the decrease of the adhesion.

For the temperature losses a simple approach is used. Initially the thermal conductivity is assumed to be 26 mW/m K and it increases linearly over 30 years to a level that is 30% higher. The losses for a pair of single pre-insulated district heating pipes are calculated according to EN 13941. A sketch of the model for improved maintenance is shown in Figure 10.1.

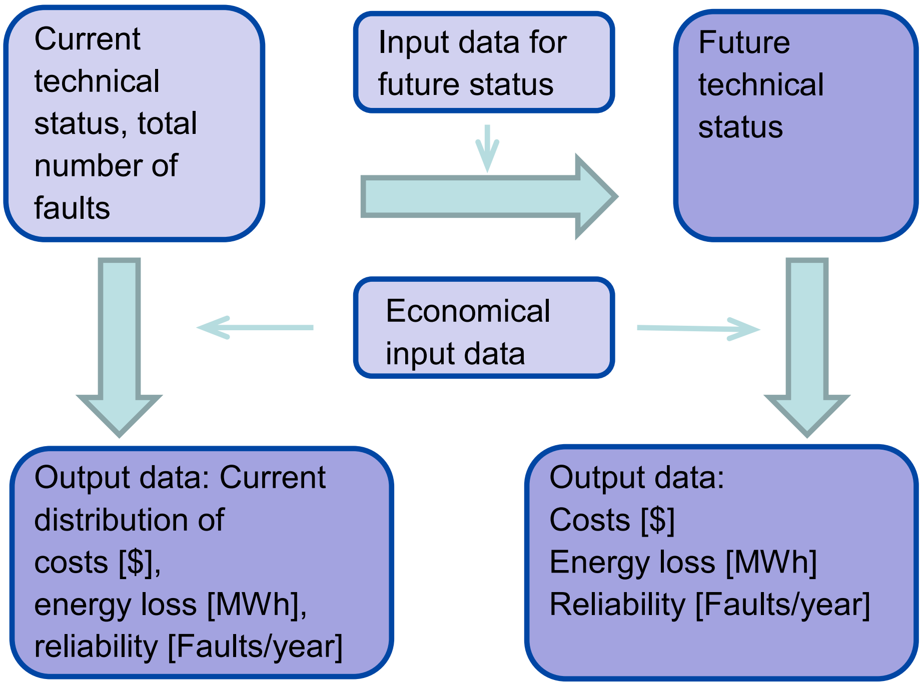

Figure 10.1: Sketch of model for improved maintenance.

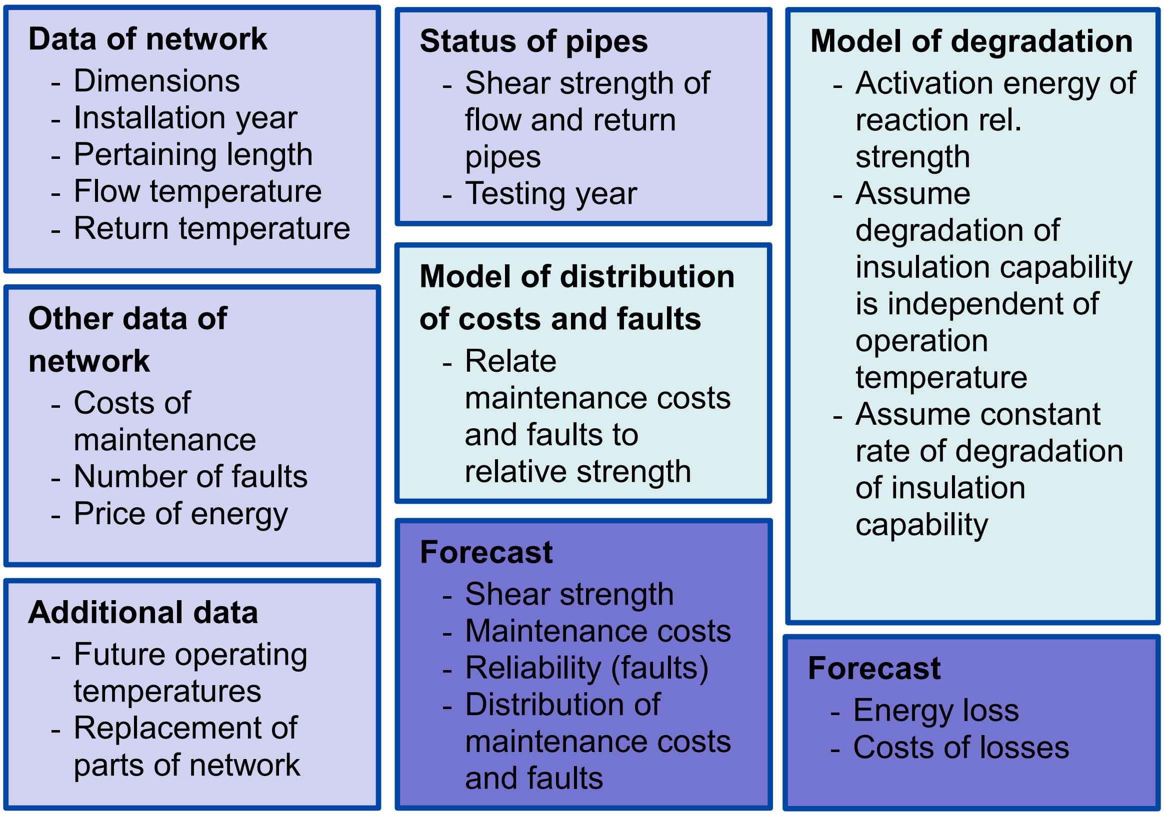

Figure 10.2: : Input and output data of model for improved maintenance.

The input data needed, the assumptions made and the forecasted data are illustrated in Figure 10.2. In order to show how development of faults related to adhesion and costs of losses in a district heating distribution network, a simplified model of the network in Goyang in Korea is used. The network has been built and expanded since 1992, and statistics are available until 2011. The nominal diameters of the pipes are in the interval from DN20 to DN850. The mean operation temperature from the power plant is 103°C in the flow pipe and the mean return temperature is 56°C. The standard deviation of both the flow and return temperature is about 5°C. The complete length of the network is 627 km. For simplicity, only three different pipe dimensions are included in the example and the expansion is assumed to have taken place at four distinct years, i.e., 1994, 1999, 2004 and 2009. The pipes have been lumped to the chosen pipe sizes and building years. Basic data are shown in Table 10.1. A temperature decrease of 6°C is assumed. The heat losses are calculated for a district heating pipes with a cover of 0.6 m and a soil temperature of 8°C. An example calculation is given in Appendix C for single pipes DN50/125.

Input data calculation estimates are given in Table 10.2. The activation energy is assumed to be 100 kJ/mol instead of the value 150 kJ/mol used in standard EN 253. Costs of heat and repair of pipes are assumed in the table.

Table 10.1: Basic data of example district heating network

Pipe section id	Dimension	Type	Installa-tion year	Length [km]	Average supply tempera-ture [°C]	Average return tempera-ture [°C]	Tempera-ture diff for losses [°C]	Heat loss new pipe [W/m]	Heat loss old pipe [W/m]
A1	DN700/800	Single	1994	85 000	103	56	79.5	166,2	197.4
A2	DN700/800	Single	1999	18 000	103	56	79.5	166.2	197.4
A3	DN700/800	Single	2004	24 000	103	56	79.5	166.2	197.4
A4	DN700/800	Single	2009	35 000	103	56	79.5	166.2	197.4
B1	DN300/450	Single	1994	163 000	100	56	78	64.5	80.1
B2	DN300/450	Single	1999	34 000	100	56	78	64.5	80.1
B3	DN300/450	Single	2004	46 000	100	56	78	64.5	80.1
B4	DN300/450	Single	2009	67 000	100	56	78	64.5	80.1
C1	DN50/125	Single	1994	82 000	97	56	76.5	29.3	37
C2	DN50/125	Single	1999	17 000	97	56	76.5	29.3	37
C3	DN50/125	Single	2004	23 000	97	56	76.5	29.3	37
C4	DN50/125	Single	2009	34 000	97	56	76.5	29.3	37
Sum				628 000					

Table 10.2: Input data for calculations

Parameter	Value	Unit
E_a	100	kJ/mol
R	8.314	J/K mol
Limit shear strength	0.12	MPa
Cost of heat	40	Euro/MWh
Average cost/fault	10 000	Euro
Conductivity of PUR	0.0259	W/mK
Final value 30 yrs	0.0337	W/mK

Table 10.3: Input data for example of district heating network in first five columns. Other columns contain calculated results for time of testing.

Pipe section id	Year of testing	Flow pipe: Shear strength [MPa]	Return pipe: Shear strength [MPa]	Actual number of faults per year and km	Relative reaction rate flow & return	Esimated initial strength [MPa]	Degrada-tion rate [MPa/ year]	Number of faults per year [-]	Costs of faults [Euro/ year]	Losses [W/m]	Value of losses per year [EURO/yr]
A1	2010	0.36	0.5	0.000030	96.53	0.50	0.009	2.6	25 500	183	2 237 962
A2	2010	0.4	0.5	0.000020	96.53	0.50	0.009	0.4	3 600	178	460 443
A3	2010	0.44	0.5	0.000010	96.53	0.50	0.010	0.2	2 400	172	595 953
A4	2010	0.49	0.5	0.000005	96.53	0.50	0.010	0.2	1 750	167	842 890
B1	2010	0.36	0.5	0.000030	74.63	0.50	0.009	4.9	48 900	73	1 709 231
B2	2010	0.4	0.5	0.000020	74.63	0.50	0.009	0.7	6 800	70	343 797
B3	2010	0.44	0.5	0.000010	74.63	0.50	0.010	0.5	4 600	68	447 915
B4	2010	0.49	0.5	0.000005	74.63	0.50	0.010	0.3	3 350	65	627 313
C1	2010	0.36	0.5	0.000030	57.46	0.50	0.009	2.5	24 600	33	394 466
C2	2010	0.4	0.5	0.000020	57.46	0.50	0.009	0.3	3 400	32	78 638
C3	2010	0.44	0.5	0.000010	57.46	0.50	0.010	0.2	2 300	31	102 142
C4	2010	0.49	0.5	0.000005	57.46	0.50	0.010	0.2	1 700	30	144 709
Sum								12.9	128000		7 985 458

In Table 10.3 feigned test data of adhesion (shear strength) are used. Repairs related to pipes are yearly between 9-22 in the district of Goyang. The failure mechanisms of these repairs are not known. In the example studied the number of yearly faults related to adhesion is assumed in Table 10.3. The relative reaction rate between flow and return is calculated. For the highest operation temperature the deterioration rate is 97 times as high for the flow pipe as compared to the return pipe. The initial strength is calculated to be the same as in the return pipe at the time of the test. The yearly deterioration rate is calculated. With the assumptions made, the number of faults or maintenance actions related to adhesion becomes 13 and the cost for these are assumed to be EUR 130 000. The losses in the network is calculated to be 200 GWh and the value is estimated to be EUR 8 000 000. The losses for this simplified network are much larger than the losses in the real network in Goyang.

Table 10.4: Input data for example of district heating network in first three columns. Other columns contain calculated forecasted results.

Pipe section id	Status for year	Assumed future tempera-ture	Relative reaction rate	Forecasted strength flow pipe [MPa]	Forcasted life until	Forecasted number of faults per year and km	Forecasted number of faults per year	Forecasted costs of faults [Euro/ year]	Forecasted losses [W/m]	Forecasted value of losses per year [EURO/yr]
A1	2030	108	1.522	0.091	2028	0.000119	10.1	100 966	204	2 500 658
A2	2030	108	1.522	0.120	2030	0.000066	1.2	11 956	204	529 551
A3	2030	108	1.522	0.132	2031	0.000033	0.8	7 971	200	691 188
A4	2030	108	1.522	0.182	2034	0.000013	0.5	4 699	195	980 859
B1	2030	105	1.532	0.088	2028	0.000122	19.9	199 437	83	1 947 254
B2	2030	105	1.532	0.118	2030	0.000068	2.3	23 113	83	406 176
B3	2030	105	1.532	0.129	2031	0.000034	1.6	15 635	81	535 262
B4	2030	105	1.532	0.179	2034	0.000014	0.9	9 147	78	753 640
C1	2030	102	1.543	0.085	2027	0.000127	10.4	103 855	38	452 841
C2	2030	102	1.543	0.115	2030	0.000070	1.2	11 871	38	93 882
C3	2030	102	1.543	0.126	2030	0.000035	0.8	8 030	37	123 492
C4	2030	102	1.543	0.176	2034	0.000014	0.5	4 732	36	176 041
Sum							50.1	501 415		9 190 843

In Table 10.4 the status of the network is forecasted year 2030. The temperature levels are assumed to be increased 5 °C on the flow pipe. This means that the reaction rate will increase by more than 50%. The forecasted shear strength is calculated based on the shear strength 2010, which is assumed to be measured, and the deterioration rate for the new temperature, which is assumed to be applied from 2010 until 2030. Here, the requirement for the shear strength is set to 0.12 MPa, which also is the criterion for end of life. The year, when end of life is reached, is also calculated. The forecasted yearly maintenance per km is calculated as the maintenance 2010 times the strength 2010 over the forecasted strength 2030. In this example, the number of faults or maintenance actions related to adhesion becomes 50 and the pertaining cost is EUR 501 000. The heat losses are estimated to increase to 230 GWh and the costs for that are estimated to EUR 9 200 000.

11 Concluding remarks

The aim of this project has been to give tools and knowledge for better maintenance planning of district heating networks of pre-insulated bonded pipes with polyurethane insulation. Deterioration of district heating pipes has been studied and a theoretical model for prediction of future status of district heating pipes has been sketched. The maintenance is focused of the failure mechanism loss of adhesion. Hence, the evaluation of the status of the pipes was done by measuring the shear strength between the PUR foam and the steel service pipe.

The results of the measured shear strength of the artificially aged pipes after various ageing periods and temperatures indicate a similar tendency of deterioration for both tangential shear strength and SP-plug test methods. The indication is clearer for the normal PE casing than the thin casing, due to fewer measured samples from the thin casing. The thin casing behaved unexpected at 140 ºC and 150 ºC by showing big gaps between the insulating PUR foam and the service pipe after ageing. These gaps mean lack of adhesion and there was no sense to measure the shear strength. The correlation factor of the results of the SP-plug and the tangential shear strength test methods from equally aged samples has been calculated to 0.74.

The results have shown that the shear strength deterioration of the pipes follows different slopes for each ageing temperature. The shear strength decreases rapidly in the beginning, then it obtains a stable level (the curve flattens out), and after that it slightly increases at the end of our experimental period. The difference between the results of the shear strength for thin and normal casing is insignificant.

Neither the raising of the ambient temperature from 10 to 70 °C nor the decreasing of the thickness of the casing from 3 mm to 0.13 mm contributed to speeding up the thermo-oxidative degradation of PUR. On the contrary our results show, that the changes of the shear strength of the pipes in the test set-up used do not depend on the thermo-oxidation of PUR, since the processes of the two different casing have the same slope and they do not continue to zero. The processes seem to have a physical character instead. The results have not shown any corroborating evidence for the existence of the Arrhenius type of relationship, and consequently do not support the calculation of the governing activation energy.

Results of the shear strength tests from supply pipes aged during one to 38 years show a slow deterioration rate. It is anticipated that the stable level is reached. The original values of the shear strength of these pipes are not available. Hence, it is difficult to say how much they have changed during the complete operation time. Regardless of variation of type of pipes and the original values of the shear strength, the results show a similar behaviour (a slow deterioration rate) as the artificial aged pipes.

Comparison of the stable level of the shear strength measured by SP-plug test for the artificially aged pipes and the naturally aged pipes shows that the value from the naturally aged pipe fit very well into the set of values from the accelerated laboratory ageing. It is clear that the stable level value of the shear strength decreases almost linearly with increasing temperature, but it is not directly dependent on the ageing time within our investigated time limit. These results represent a strong indication that the ageing process is of a physical nature and not a result of an oxidation process. There is a need for further studies of the insulation PUR material and the morphology of it in the pipe system, and the various processes linked to the different slopes of the shear strength deterioration.

The project has provided a framework for forecasting future technical status, maintenance needs and energy losses based on known technical status, today's maintenance needs and estimated future operating temperatures. The maintenance activities of the distribution system are based on the technical status. The theoretical calculations and information from Korea and Norway DH-pipe networks have been used for demonstrating the model.

In the framework, the failure mechanism is considered as loss of adhesion between polyurethane and the service pipe. The deterioration of the adhesion is assumed to be a thermo-oxidative process governed by an Arrhenius relationship. Our hypothesis of a physical deterioration mechanism is not yet proven and therefore is not used here. In order to show how the development of faults related to adhesion and costs of heat losses in a district heating distribution network, a simplified model of the network in Goyang in Korea was used.

The model has been used to forecast the status of the network in the year 2030. The temperature levels in the flow pipe were assumed to increase by 5 °C. This means that the reaction rate will increase by more than 50%. In the scenario discussed, the forecasted shear strength has been calculated based on the shear strength 2010, which was assumed to be measured, and the deterioration rate for the new temperature, which was assumed to be applied from 2010 until 2030. Here, the requirement for the shear strength was set to 0.12 MPa, which also is the criterion for end of life. The year, when end of life is reached, has also been calculated. The forecasted yearly maintenance per km has been calculated as the maintenance 2010 times the strength 2010 over the forecasted strength 2030. In the example treated, the number of faults or maintenance actions related to adhesion is increased by a factor of 3.9. The heat losses are estimated to increase by 15%.

Figures

Tables

Equations

Abbreviations

(in alphabetic order)

CHP	Combined Heat and Power
DHC	District Heating and Cooling
HDPE	High Density Polyethylene
IEA	International Energy Agency
PE	Polyethylene
PUR	Polyurethane
SP	Technical Research Institute of Sweden

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Appendix A: Calculation of shear stress according to EN13941:2009

Single pipe DN 100/225

Laying temperature	$T_0 := 0°C$	
Flow temperature	$T_f := 150°C$	
Outside diameter	$D := 114.3mm$	
Material thickness	$t := 3.6 \cdot mm$	
Inside diameter	$d := D - 2 \cdot t$	
Young's modulus	$E := 210 \cdot GPa$	$\nu := 0.3$
Expansion coefficient	$\alpha := \frac{11}{10^6 °C}$	
Cross-sectional area	$A_s := \frac{\pi}{4} \cdot (D^2 - d^2)$	
Fixing force	$F_g := E \cdot A_s \cdot \alpha \cdot (T_f - T_0) = 433.695 kN$	$\frac{F_g}{A_s} = 346.405 MPa$
Circumference	$L_c := \pi \cdot D = 359.084 mm$	
Density of water	$\rho_w := 1000 \cdot \frac{kg}{m^3}$	
Weight	$m_s := 15 \cdot \frac{kg}{m}$	$G_s := m_s \cdot g$
	$G_w := \rho_w g \cdot \pi \cdot \frac{d^2}{4}$	
Casing diameter	$D_c := 225 \cdot mm$	
Friction	$\mu := 0.6$	
Cover	$H_c := 2000 \cdot mm$	
Depth	$Z := H_c + \frac{D_c}{2} = 2.112 \times 10^3 \cdot mm$	

Weight density of soil $\gamma_s := 18 \frac{kN}{m^3}$

Soil pressure $\sigma_v := \gamma_s \cdot Z$ $\sigma_v = 38.025 \, kPa$

Soil pressure coefficient $K_0 := 0.5$

Friction per length $F_u := \mu \cdot \left(\frac{1 + K_0}{2} \cdot \sigma_v \cdot \pi \cdot D_c + G_s + G_w - \gamma_s \cdot \frac{\pi \cdot D_c^2}{4} \right) = 11.807 \cdot \frac{kN}{m}$

Pressure $p := 16 \cdot bar$

Hoop stress $\sigma_p := \frac{p \cdot d}{2 \cdot t} = 23.8 \cdot MPa$

Friction length $L_f := \frac{1}{F_u} \cdot \left[\left(\frac{1}{2} - \nu \right) \cdot \sigma_p A_s + E \cdot A_s \cdot \alpha \cdot \left(T_f - T_0 \right) \right] = 37.237 m$

Shear stress $\tau := \frac{F_g}{L_c \cdot L_f} = 32.435 \cdot kPa$

Quotient $\frac{\tau}{0.12 \cdot MPa} = 0.27$

Appendix B: Regression curves for accelerated aged pipes

Regression curves are given in Figures B1-B4. Slope of regression curves given in Table B 1, with confidence intervals with 95% outcome.

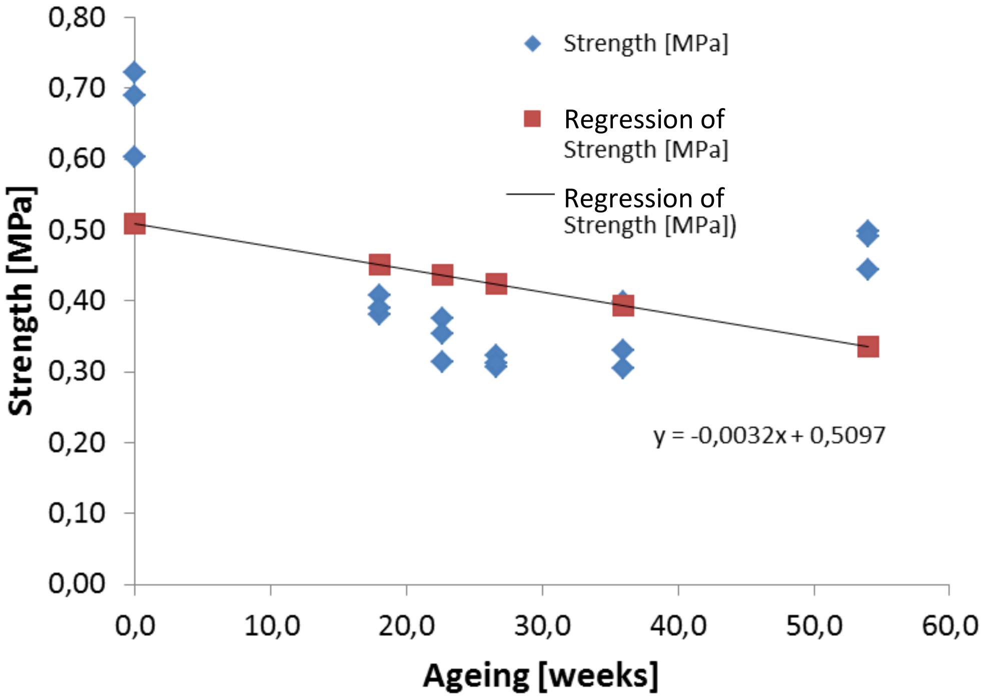

Figure B 1: Linear regression curve for accelerated aged pipe with thin casing at 130 °C.

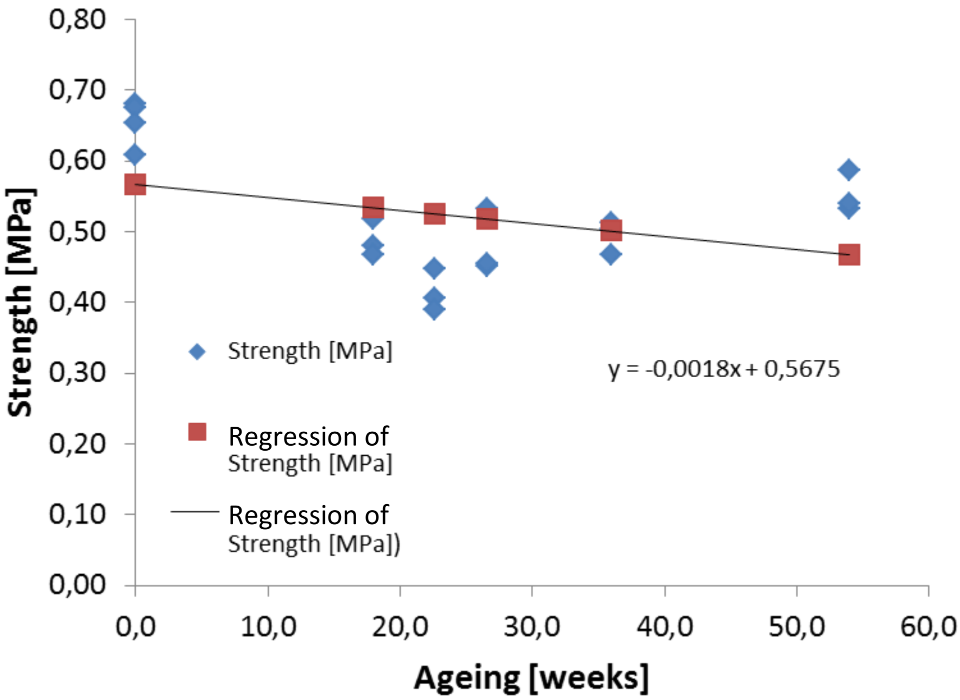

Figure B 2: Linear regression curve for accelerated aged pipe with normal casing at 130 °C.

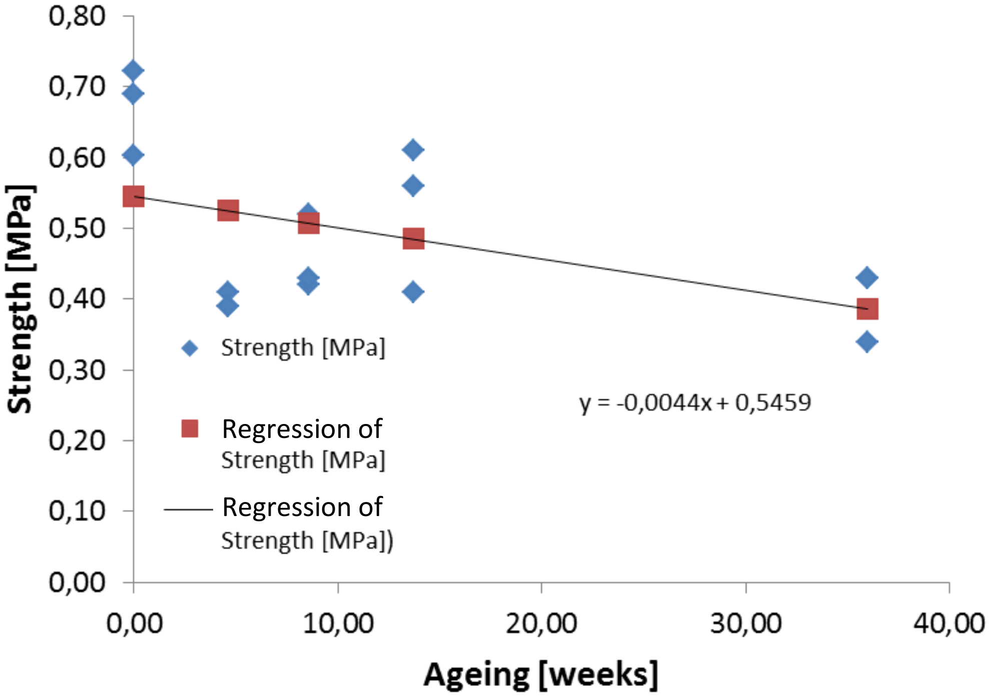

Figure B 3: Linear regression curve for accelerated aged pipe with thin casing at 140 °C.

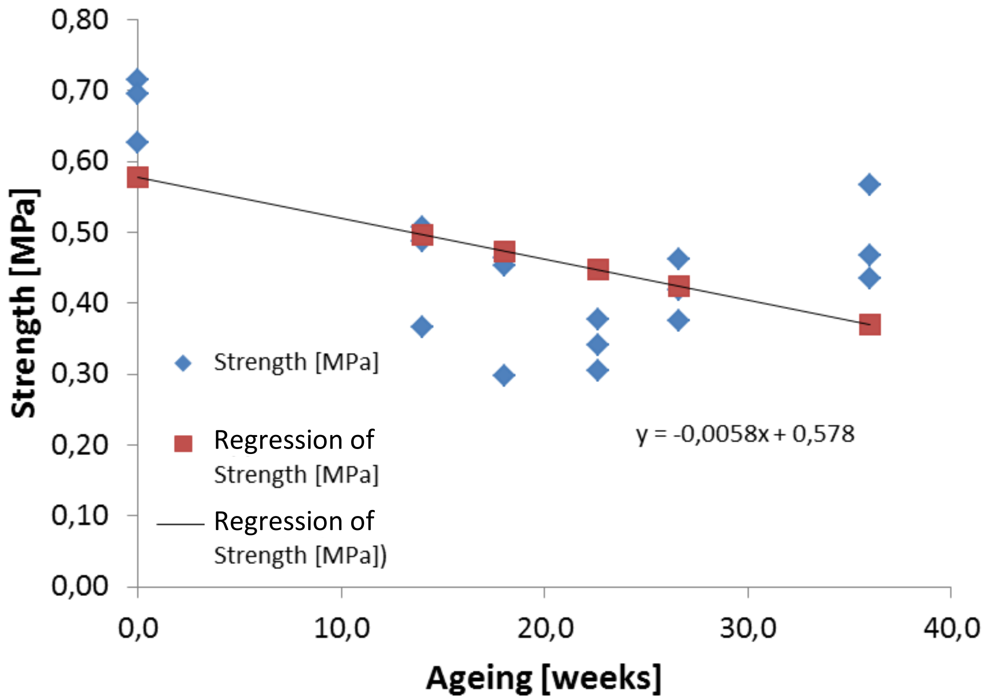

Figure B 4: Linear regression curve for accelerated aged pipe with normal casing at 140 °C.

Table B 1: Slope of deterioration curve and confidence intervals for 95% outcome

Tempera-ture [°C]	Casing	Slope	Lower 95%	Upper 95%
130	Thin	-0,00323	-0,00688	0,000428
130	Normal	-0,00184	-0,00416	0,000475
140	Thin	-0,00441	-0,00922	0,000392
140	Normal	-0,0058	-0,01052	-0,00108

Appendix C: Calculation of heat losses

Regular DN 50 DH pipes

Calculations in accordance with SS-EN 13941:2009.

Pipe geometry

Service pipe diameter: $D_s := 60.3 \cdot mm$

Casing pipe diameter: $D_c := 125 \cdot mm$

Casing pipe wall thickness: $s_c := 3.0 \cdot mm$

Trench geometry

Fill height: $H_0 := 0.6 \cdot m$

Laying depth: $Z := H_0 + .5 \cdot D_c = 0.663\ m$

Distance between pipes: $C_0 := 250 \cdot mm$

Centre line distance: $C_1 := C_0 + D_c = 0.375\ m$

Material parameters

Thermal conductivity of PUR: $\lambda_i := 0.0259 \cdot W \cdot m^{-1} \cdot K^{-1}$

Thermal conductivity of soil: $\lambda_S := 1.5 \cdot W \cdot m^{-1} \cdot K^{-1}$

Service parameters

Flow temperature: $T_f := (273 + 98) \cdot K = 371\ K$

Return temperature: $T_r := (273 + 56) \cdot K = 329\ K$

Undisturbed soil temperature: $T_S := (273 + 8) \cdot K = 281\ K$

Thermal parameters

Soil surface insulance: $R_0 := 0.0685 \cdot m^2 \cdot K \cdot W^{-1}$

Soil insulance:

$$R_S := \frac{1}{2 \cdot \pi \cdot \lambda_S} \cdot \ln\left[\frac{4 \cdot \left(Z + R_0 \cdot \lambda_S\right)}{D_c}\right]$$

$$R_S = 0.339 \cdot m \cdot K \cdot W^{-1}$$

PUR foam insulance:

$$R_i := \frac{1}{2 \cdot \pi \cdot \lambda_i} \cdot \ln\left(\frac{D_c - 2 \cdot s_c}{D_s}\right)$$

$$R_i = 4.177 \cdot m \cdot K \cdot W^{-1}$$

Heat exchange insulance:

$$R_h := \frac{1}{4 \cdot \pi \cdot \lambda_S} \cdot \ln\left[1 + \left[\frac{2 \cdot \left(Z + R_0 \cdot \lambda_S\right)}{C_1}\right]^2\right]$$

$$R_h = 0.152 \cdot m \cdot K \cdot W^{-1}$$

Heat loss coefficients:

$$U_1 := \frac{R_S + R_i}{\left(R_S + R_i\right)^2 - R_h^{\,2}} = 0.222 \frac{m \cdot kg}{K \cdot s^3}$$

$$U_2 := \frac{R_h}{\left(R_S + R_i\right)^2 - R_h^{\,2}} = 7.475 \times 10^{-3} \frac{m \cdot kg}{K \cdot s^3}$$

Overall heat loss:

$$\Phi_R := 2 \cdot \left(U_1 - U_2\right) \cdot \left(\frac{T_f + T_r}{2} - T_S\right)$$

$$\Phi_R = 29.557 \cdot W \cdot m^{-1}$$