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Optimal conditions for accelerated thermal ageing of district heating pipes

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Abstract

Technical lifetime prediction of polymeric materials is often based on accelerated ageing tests at elevated temperatures. Samples are exposed to relatively high temperatures to accelerate the natural degradation processes. For district heating pipes, accelerated thermal ageing is the ordinary method used to determine the lifetime of pipes. According to the Standard EN 253:2009 + A1:2013, the district heating pipes shall be subjected to an accelerated thermal ageing for a long period of time at 160 ˚C or 170 ˚C. The lifetime is determined by extrapolation using the Arrhenius relationship. However, papers published recently have questioned this method, especially the high temperatures used for ageing of the pipes and the use of Arrhenius equation to describe the complicated degradation mechanisms, which can result in the erroneous estimation of the technical lifetime.

Our investigation has shown the complexity of the pipe's degradation mechanisms. The behaviour of mechanical shear strength at elevated temperatures (T > 130 °C), suggests an alteration rather than an acceleration of the degradation mechanisms. Accelerated ageing tests should reproduce the proper natural ageing mechanisms. The analyses of PUR's thermal conductivity and its chemical structure by FTIR confirmed the degradation patterns.

Keywords: Degradation mechanisms; district heating pipes; rigid polyurethane foam; accelerated ageing

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1. Introduction

New elements have been introduced to the district heating (DH) systems looking for more sustainable networks. Integration of renewable energies into the DH networks is a reality which has been possible due to the use of better insulation materials in new buildings. In the last years, a new generation of DH technology has been discussed. The 4th generation of DH system (4GDH) integrates different energy systems and operate at lower temperatures in combination with low-energy buildings. It means smarter distribution networks looking for synergies between several energy sources [1]. This development seems like a natural and needed improvement of DH networks to become more efficient. However, the current DH networks should be improved to deal with future issues. Today, there is almost 600 000 km of distribution pipes from older generations, especially from the third generation, around the world today [2]. A big challenge is to understand the DH pipes' deterioration which would be helpful for the urban and energy planning activities for the future.

The standard method used today for lifetime prediction of DH pipes is based on accelerated thermal ageing at relatively high temperatures and evaluation of the mechanical shear strength during the ageing period. Then, an Arrhenius relationship is applied to extrapolate the results to the average operating temperature. Recently, researchers have pointed out that thermal ageing at relatively elevated temperatures alters the degradation mechanisms rather than accelerate them as mentioned in [3,4]

The first part of our investigation focused on the degradation mechanisms of rigid polyurethane (PUR) foam [5]. The main aim of the second part was to understand the degradation mechanisms of PUR in DH pipes aged artificially. We studied the ageing effects on the pipes' mechanical and thermal performances, which are of vital importance for the correct functionality of the DH networks. Non-standard methods were used to measure both thermal and mechanical properties. Fourier Transform Infrared (FTIR) analyses were performed to study the changes of PUR chemical composition and the ageing effects.

2. Experiments

Four DH pipes were instrumented with thermoelements type K and transient plane sources (TPS) sensors for measurements of temperature and thermal conductivity, respectively. The pipes were placed in a controlled temperature chamber at 23 °C. Three pipes were connected to controllers to heat up the service steel pipe to the corresponding ageing temperatures, 130, 150 and 170 °C. The remaining pipe was kept at room temperature, and the reference measurements were performed on it.

The SP plug method, described in [6], was used to measure the pipes' mechanical shear strength. The pipes could cool down to room temperature first before the mechanical tests were performed. Three samples were taken from each pipe, every test occasion.

A TPS method was used to measure the thermal conductivity of the pipes. The measurements were performed first at the ageing temperature and then before the mechanical test at room temperature. The TPS method is a standard method [7], but it is not generally applied for pipe application and in the DHPs' branch. In this case, two TPS sensors were installed in each pipe at two different distances from the steel service pipe, 5 and 30 mm, respectively.

Some PUR samples collected from the aged DHPs were selected to a more in-depth analysis of their chemical structure using the attenuated total reflection (ATR) technique in an FTIR equipment. The samples had a thickness of approximately 2 mm.

3. Results

The mechanical tests were performed firstly after 1, 2, 3, 6, 8, 15, 21 and 30 days, after this period every 30 days. The SP plug method evaluates the residual shear strength between PUR and the steel service pipe. During the first stage of ageing, the mechanical strength dropped down to a local minimum and then it went up to a maximum point. The change's rate depends on the ageing temperature, occurring faster at higher temperatures. After the local maximum was reached for every ageing temperature, the mechanical strength tended to decrease to zero. However, the pipe aged at 130 °C showed another behaviour after 10 000 hours. The strength dropped to 65 – 70 % of the original value and remained constant for an extended period. Interestingly, this result means that a linear Arrhenius relationship cannot be applied to calculate the DHP lifetime, as the standard EN253 describes [8]. The results were normalised using the first values obtained after 24 h and are shown in Fig. 1.

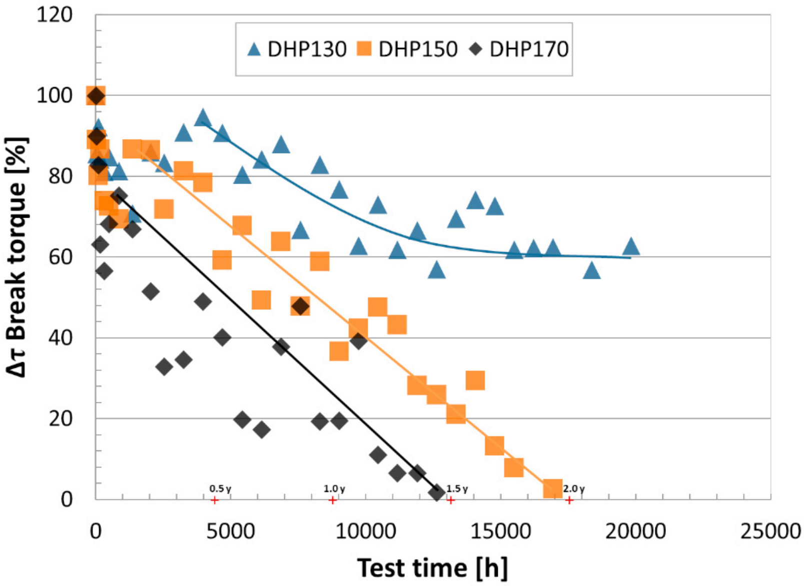

Fig. 1. Mechanical shear strength measured by the SP plug method.

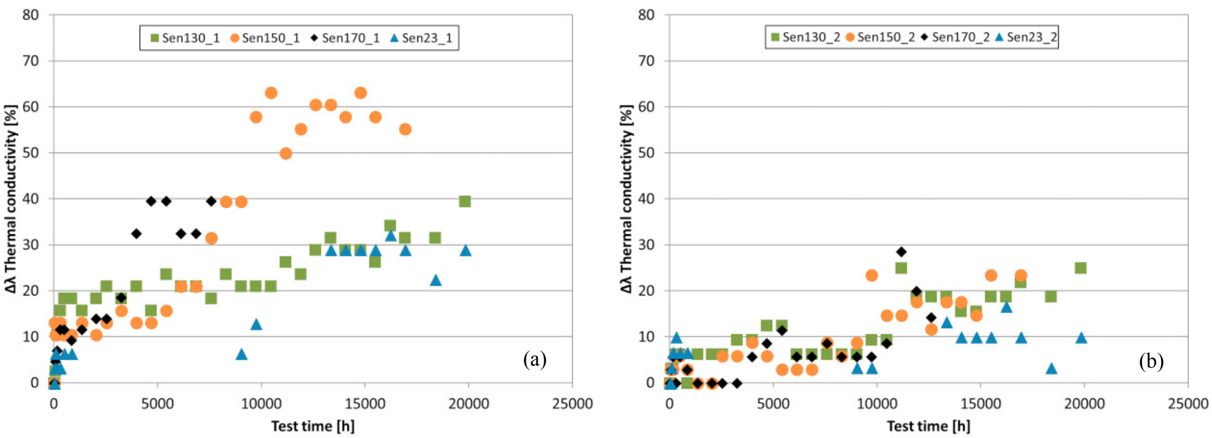

Fig. 2. Thermal conductivity measurements. (a) Δλ measured by the sensor positioned at 5 mm and (b) 30 mm in each pipe.

Table 1. Temperatures measured by the TPS sensors at their locations, 5 and 30 mm from the steel service pipe.

Ageing temperature (°C)	Temperature at 5 mm (°C)	Temperature at 30 mm (°C)
130	97-100	55-60
150	112-114	67-71
170	130-141	76-86

The thermal conductivity (λ) was measured first at the corresponding ageing temperatures and then at room temperature, by TPS sensors located at two different distances from the steel service pipe, which means that the PUR foam was exposed to lower temperatures at these locations than the chosen ageing temperatures as shown in Table 1.

Following the change of this property at different temperatures was possible. The curves in Fig. 2 behave similarly, but the λ values increased rapidly at temperatures higher than 130 °C. It is well-known that λ values for DH pipes are affected mainly due to gas transport, depending on the foam morphology and the HDPE casing pipe [4]. The gas exchange process seemed to be the dominant mechanisms at the places where the temperature was not higher than 100 °C. However, another process might be activated besides gas diffusion at T > 130 °C. Alteration of the cell morphology and losses of cyclopentane, due to thermo-oxidative degradation, may cause deterioration of the insolation performance at these temperatures.

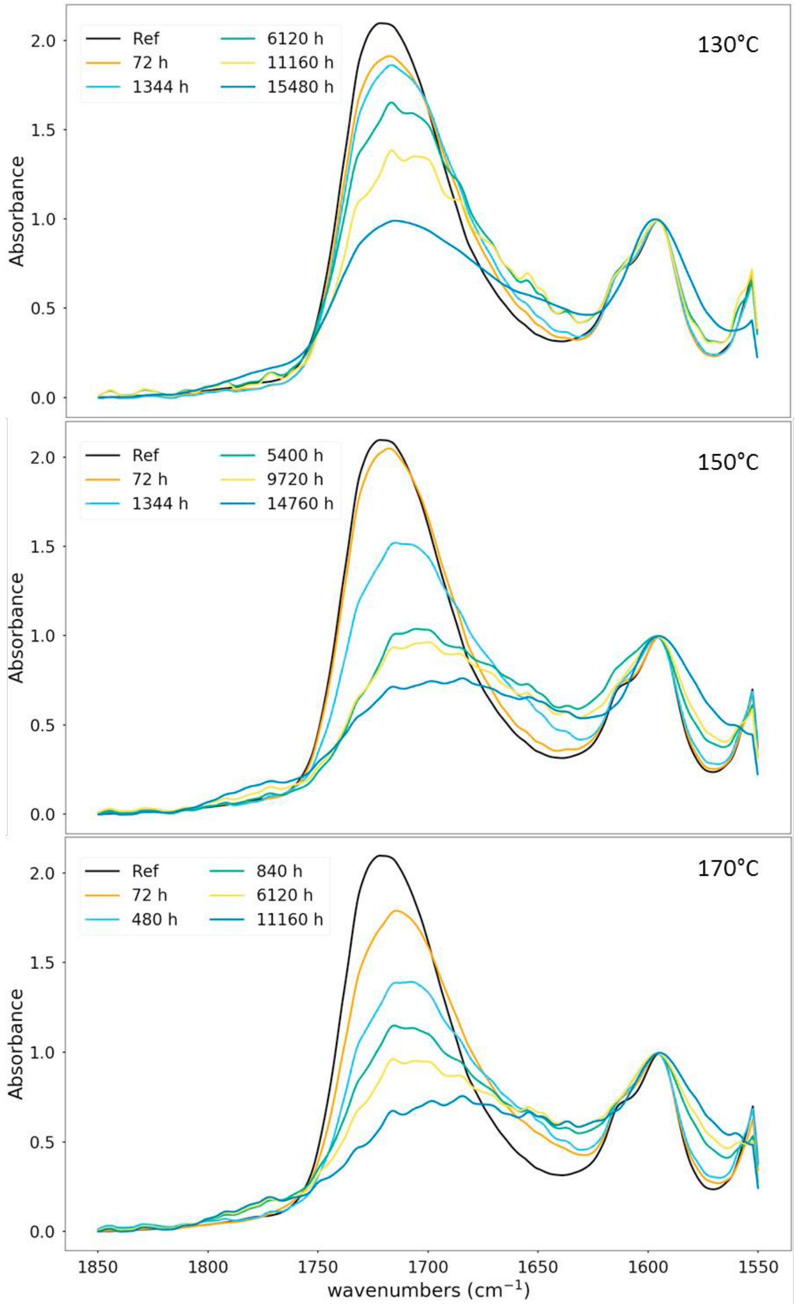

Fig. 3. FTIR spectra showing the new carbonyl peaks formed because of oxidation processes.

Ageing caused changes in the chemical structure of the foam, which affect the mechanical and thermal performance of the pipes. These changes were identified using FTIR spectroscopy, pointing out the most interesting peaks. In Fig. 3, a part of the FTIR spectra shows the loss of urethane (C=O) group around 1712 cm^{-1}. This change was mainly due to thermo-oxidative degradation. This phenomenon is temperature-dependent, occurring very rapidly at higher temperatures. Also, a new carbonyl group appeared in the range 1760 – 1790 cm^{-1} as a result of the oxidation process [4].

4. Conclusion

Accelerated thermal ageing of DH pipes at elevated temperatures was performed, observing the activation of different degradation mechanisms and deterioration of the pipes' performance. It seemed to be a combination of several processes, that hardly can be described by a linear Arrhenius relationship, as proposed in the European Standard EN253. For this reason, the lifetime prediction becomes a complex task due to the different factors that affect the measurements.

Additionally, all tests performed in this study demonstrate that the degradation mechanisms at high ageing temperatures, T > 130 °C, differed significantly from the results obtained at lower temperatures. It means that some ageing processes activated at high temperatures are unusual for the normal operation of DH networks and can lead to an incorrect estimation of the pipes' lifetime.

An improved ageing methodology is needed to obtain reliable lifetime prediction, which can have a significant impact on the general urban planning in a city. It includes decisions for new systems and replacement or extension of the existing systems. It is essential not only for the energy companies but also for social, educational and cultural infrastructures.

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