Pipeopsy: A Novel Method for Status Assessment of District Heating Pipes in Operation

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Abstract: This study presents a novel status assessment method for district heating (DH) pipelines in operation, which we call "Pipeopsy" (a biopsy for pipes). The method evaluates adhesion strength between the service pipe and polyurethane (PUR) insulation, which is a crucial property for the durability of DH pipes and the extent of degradation of PUR foam closest to the service pipe. This method is based on three parts: (1) measuring adhesion strength and taking samples of the foam, (2) analyzing the foam in a laboratory using Fourier-transform infrared (FTIR) spectroscopy, and (3) restoring pipeline by replacing the foam and sealing the casing by welding polyethylene plugs in the holes. Temperature dependence and measurement accuracy of the shear strength test method have also been examined, as well as correlation with the standard axial shear strength test method. The shear strength of the aged pipes shows no temperature dependence, while the quotient between the value produced with the plug method and axial method is 3.1. Compared with the standard test methods, the advantages of Pipeopsy involve small cost, less damage to pipes, and the use of simple mobile tools for taking samples and performing measurements. Importantly, testing can be performed without shutting down the operation of DH pipelines. Furthermore, the method provides not only the information on adhesion strength but also information on the extent of chemical degradation in PUR. This combination of information provides a more detailed picture of the status of pipes and can be used to make a prediction about the remaining lifetime. Pipeopsy produces many results in a short time, and better statistics, which provide a solid basis for decision-makers focused on the maintenance of DH pipes or for applying artificial intelligence. **DOI: 10.1061/JPSEA2.PSENG-1689.**

Practical Applications: District heating (DH) pipes consist of a steel pipe surrounded by insulating foam and a casing. This design requires satisfactory adhesion between the components to achieve good long-term performance. The use of DH pipes in a reliable and cost-effective way as long as possible requires planned and selective replacement of worn-out parts. A prerequisite to accomplish this is reliable information about the functional status and remaining service life of different parts of existing networks. Pipeopsy is a new field test method that provides valuable information on whether adhesion strength between insulation foam and steel pipe is at a satisfactory level. In addition, chemical analysis provides information on the degree of degradation of the foam closest to the steel pipe. If a similar return pipe can be evaluated, conclusions can be drawn about the extent of reduction in adhesion and whether it is due to degradation of the insulation foam. With this information, the remaining lifetime of the supply pipe can be estimated. Using the Pipeopsy method, testing can be performed at a small cost, using simple mobile tools and without shutting down the operation. Therefore, this method is the only one of its kind that can be used on a large scale.

Author keywords: District heating pipelines; Status assessment; Durability; Adhesion strength; Infrared spectroscopy.

Introduction

Roughly 50 years ago, prefabricated district heating (DH) pipes were introduced, and today, they are the type most used in DH networks. DH pipes comprise an inner pipe (service pipe), which is normally made of steel, surrounded by polyurethane (PUR) foam insulation and an outer high-density polyethylene (HDPE) casing for protection. This design requires good adhesion between the components to achieve good mechanical and thermal performance over a long operating time.

Loss of adhesion, especially between the PUR insulation and the service pipe, is the most critical failure mechanism. When the adhesion strength (shear strength) is lost, the service pipe can move freely due to temperature fluctuations in the DH system during operation. Movements of the service pipe, due to thermal expansion, can result in mechanical fatigue and fracture, especially close to bends. The loss of adhesion between the PUR and the service pipe is mainly related to the aging process of PUR and poses a serious social and economic threat for the exploitation of DH systems. The interface between the steel pipe and the PUR foam is the most exposed part of the pipe because the temperature in the foam is at its maximum. Furthermore, the insulation in the bends can be compressed and broken by the service pipe, which can lead to damage of the casing and its joints. In turn, this means that the PUR is not

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protected against ambient conditions, which, in most cases, is water. When water leaks through service pipes and/or casing pipes, long sections of the insulation can be destroyed by hydrolytic degradation. The failure of DH pipe construction is an issue that needs to be addressed.

There are strong economic and environmental reasons to continue to use existing DH networks in a reliable and cost-effective way; however, this way demands planned, efficient, and selective replacement of worn-out parts (Hay et al. 2023). A prerequisite to accomplish this is reliable information about the functional status and remaining service life of different parts of existing DH networks, which in turn requires access to reliable field test methods for status monitoring and assessment of remaining service life. As noted, the most important property that reflects the functional status of pipes is the adhesion strength between the PUR and the service pipe. According to the European standard EN 253:2019 (5.4.1) (CEN 2019b), which is usually used for quality assurance of newly manufactured DH pipes, the adhesion strength should be measured as axial shear strength on three pieces of pipe with a minimum size of 200 mm using a universal testing machine. However, for practical and financial reasons, this method is not viable as a field method for status assessment and is rarely used in practice, more specifically because of the high costs of excavation, pipe cutting, repair, and restoration. In addition, the supply of heat needs to be turned off during a long testing period. One of the very few studies of this type is the work by Hay et al. (2021). They cut out four sections of the Duisburg DH network in Germany and a bend compensation element. The properties of these sections were then evaluated in the laboratory. They concluded that different components of the DH pipe can be expected to have different remaining service lives and that deterioration of the PUR will limit the pipe's service life. Lidén and Adl-Zarrabi (2017) found that there are no nondestructive methods to determine the performance of existing DH pipes in operation. In two other articles, they used a test method based on cooling where the temperature decline in the pipe network is measured after shutdown. In the first article, they utilized the copper wire, which is already embedded in the insulation, as a sensor for measuring the temperature (Lidén and Adl-Zarrabi 2020). In the second article, they concluded that the drainage valves could be used to measure the temperature decline in the pipe network after shutdown, and that the results might be usable for predicting the thermal status of the pipe (Lidén et al. 2021). In summary, there are very few scientific articles in this area, and we have not found any proposal for a field method that is feasible from a practical and economic perspective.

This paper describes a novel fast, reliable, and cost-effective field method called "Pipeopsy" (a biopsy for pipes), which was developed at RISE (Research Institutes of Sweden) in a recent project for status assessment of DH pipes in operation without disrupting operations. The field method is based on a previously reported laboratory method by Sällström et al. (2012) called the "RISE plug method," which was further developed and fitted into a field method within the framework of the recent project. In the plug method, a cylindrical test specimen (plug) is created within the pipe by two hole-drills: a larger with an outside diameter of 38 mm and a smaller with an inside diameter of 27 mm. In this way, a cylindrical specimen is created with the PUR foam still connected to the service pipe. In the next step, an aluminum pipe with an inside diameter of 27 mm is glued to the plug. After a short curing period, a torque is applied and recorded by a static torque sensor until the test specimen becomes loose or breaks.

The Pipeopsy field method consists of three steps: (1) measurement of the adhesion strength (shear strength) between the PUR insulation and service pipe; (2) chemical analysis of the removed insulation using Fourier-transform infrared spectroscopy (FTIR) in the laboratory; and (3) restoration of the pipeline by replacing the removed PUR insulation and sealing the HDPE casing after testing.

Thanks to the proposed method, testing can be performed at a small cost, using simple mobile tools and without shutting down the operation.

Experimental

RISE Plug Method

The RISE plug method measures the adhesion strength between insulation and service pipe. The torque and the angle of rotation are measured when the plug is loosened. In this project, a test rig designed for field measurements was developed that allows support and steering for both cutting out samples and torque measurement. The rig is fixed on the casing by supports and suction cups with negative pressure. A combined torque wrench and sensor, supported via an arm linked to the rig, is used in the test (Fig. 1).

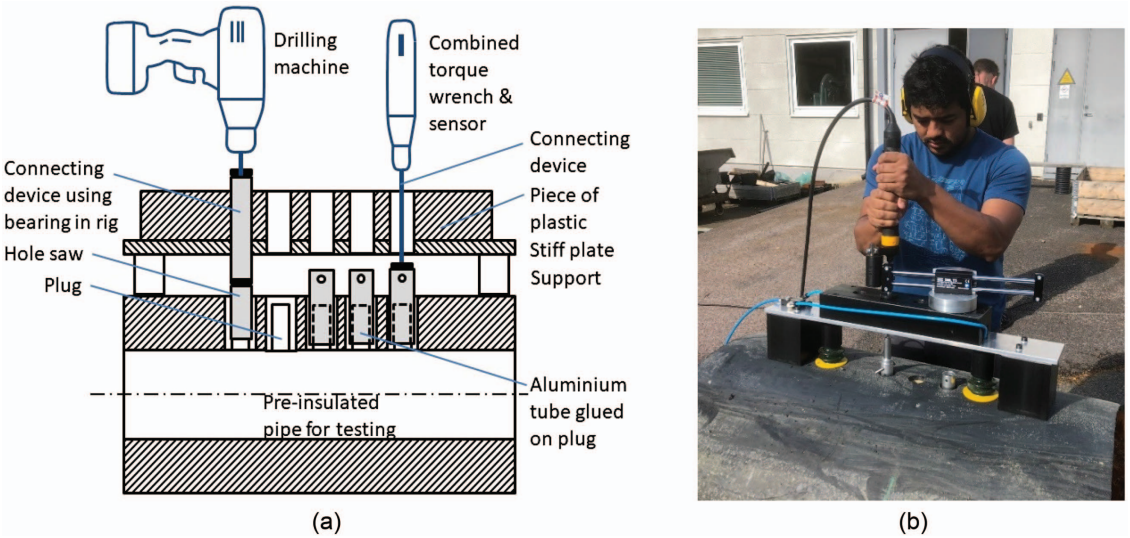

Fig. 1. (Color) Sketch of: (a) the plug method; and (b) measurement using the test rig.

The calculation of the shear strength τ_u [Pa] is based on the torsion of a circular axle with a linear elastic material. For an axle (in this case, the plug), the shear stress will then vary linearly with the radius and the maximum shear stress will occur at the circumference of the plug for the radius $d/2$. This maximum shear stress is interpreted as the shear strength τ_u [Pa]. When the plug with the diameter $d = 0.027$ m is twisted loose with the applied and measured maximum torque M [Nm], the shear strength τ_u [Pa] becomes [see, e.g., the textbook by Timoshenko and Goodier (1970)]

$$\tau_u = \frac{16M}{\pi d^3} \tag{1}$$

To obtain a good statistical basis and low measurement uncertainty for the average value, at least seven plugs were required. To reduce variation in measurement results, samples were taken close together along a generatrix. A lower limit of shear strength is also reported based on the calculated extended measurement uncertainty with two standard deviations and assuming normal distribution of the measurement results. With 97.5% probability, the actual shear strength is greater than the specified lower limit. With 95% confidence, the actual average value of the shear strength is expected to be within the range

$$\tau_{avr,ci} = \tau_{avr} \pm t_{97.5\%,N-1} \times \frac{\tau_{std}}{\sqrt{N}} = \tau_{avr}(1 \pm U_\tau) \tag{2}$$

The increased measurement uncertainty is defined as

$$U_\tau = t_{97.5\%,N-1} \times \frac{\tau_{std}}{\tau_{avr}\sqrt{N}} \tag{3}$$

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

FTIR Analysis

Degradation of PUR leads to several alterations of the chemical structure. Our previous work demonstrated that degradation of PUR foam due to aging can successfully be identified and quantified by FTIR spectroscopy analyses as reported by Yarahmadi et al. (2017) and Vega et al. (2018). It is especially important to measure the loss of functional groups such as urethane linkage (peak at around 1,712 cm^{-1}) and the N-H bending vibration band at 1,512 cm^{-1}, which can be attributed to the degradation of urethane links by oxidation (Colin et al. 2015). FTIR analysis is used as an integral part of our proposed method for evaluating changes in the chemical structure of the PUR insulation foam. The FTIR spectra of PUR are shown in Fig. 2.

To quantify the changes, the relative functional group concentrations were determined by normalizing the assigned band intensity to the intensity of the methylene diphenyl diisocyanate aromatic ring deformation [aromatic (C═C) vibration] at 1,595 cm^{-1}, which is frequently used as the internal reference (Modesti and Lorenzetti 2001). FTIR analysis was performed on the plugs obtained from the field measurements. Two thin samples (1–2 mm) were taken from each plug for analysis, one from the end that has been in contact with the service pipe ("downside") and one from the opposite end ("upside"), as shown in Fig. 3. The contact surface of the downside plug is the most degraded because it is exposed to the highest temperature, whereas the upside plug is located ~20 mm from the downside plug and is consequently exposed to a much lower temperature; therefore, the upside plug is regarded as the internal reference. The reduction in the carbonyl peak at around 1,712 cm^{-1} and the N─H bending vibration peak at 1,512 cm^{-1} was used as indicators of degradation.

Results and Discussion

Measurement of Adhesion Strength in the Field

The test method currently available is the standard test method described in EN 253. According to EN 253, the axial shear strength shall be determined using three test specimens no less than 200 mm

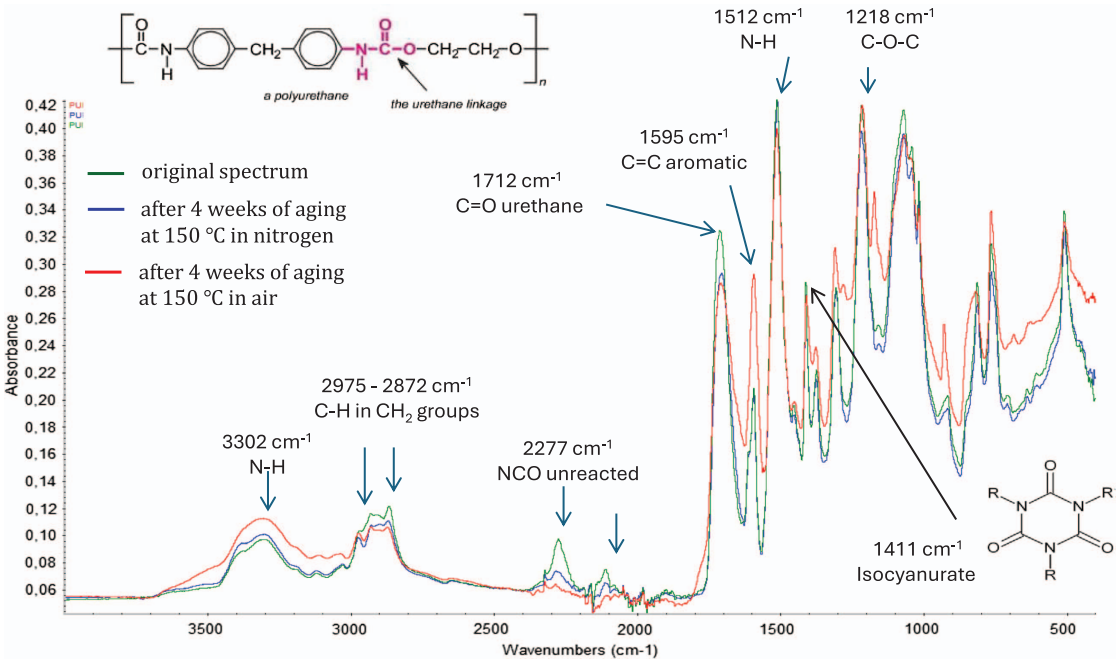

Fig. 2. (Color) FTIR spectra of PUR foam with the characteristic peaks indicated by arrows.

Fig. 3. (Color) (a) PUR plugs obtained from the return and flow lines; and (b) a PUR slice from the plug on the ATR module of the Nicolet FTIR equipment.

in length that are cut perpendicular to the axis of the pipe. An axial force is than applied until they break. There are several disadvantages with this method as a field test method. First, the method requires large specimens, which means extensive interference in the operation of DH pipes, especially considering that operations must be stopped for a longer period. Second, the method does not really measure adhesion strength because the shear plane propagates through the insulation in different unpredictable ways (Weidlich et al. 2018). Third, only a few samples can be tested, which means insufficient statistical basis.

The advantages and usability of the proposed method were examined in the field under real conditions. In some cases, the testing took place in the field during pipeline operation or when the network was shut down; in other cases, testing was conducted in the laboratory on pipe pieces removed from a DH pipeline. The results of field measurements are presented in Table 1. Laboratory testing was performed at 23°C. At lower temperatures, the pipeline was shut down, and at higher temperatures, the pipeline was in operation.

Field measurements can be performed at various temperatures. Because the shear strength can vary with temperature, the temperature dependence of the shear strength was investigated using a virgin DH pipe (dimension DN50/Ø 140 mm), as well as with two similar pipes that had been subjected to accelerated aging at 140°C for 310 and 490 days, respectively. The intention was to evaluate temperature dependence for both virgin pipes and aged pipes that had already reached the plateau phase; that is, a constant level of shear strength over a long time (Vega et al. 2018). The temperature dependence of the shear strength as measured by the plug method was investigated using five temperature levels: 23°C, 60°C, 80°C, 100°C, and 120°C. The pipes were heated with an electric current to the desired temperature level and allowed to stabilize over 1–2 h prior to testing. At least seven samples were taken next to each other on a generatrix along the pipe. The test results are shown in Fig. 4.

The virgin (unaged) pipe shows a clear tendency of a reduced shear strength with increased test temperature with a difference of ~25% between the test at 23°C and 120°C. The aged pipes show a reduced shear strength compared with the virgin pipe, which agrees with our previously reported results (Vega et al. 2018, 2020), but the shear strength of the aged pipes does not show any temperature dependence. For the pipe aged 310 days, the measurement uncertainty became high with only 6–7 samples at each temperature. For the virgin pipe and the pipe aged 490 days, twice as many tests were performed at each temperature, and a smaller measurement uncertainty was obtained.

Table 1. Results of the field and laboratory measurements

	Date	Year	Temperature at testing (°C)		Average shear strength (MPa)		Measurement uncertainty (%)		Lower limit shear strength (MPa)	
Place	Testing	Inst.	Flow	Return	Flow	Return	Flow	Return	Flow	Return
Linköping	September 17, 2019	1996	6	6	0.58	0.59	24	40	0.44	0.35
Jönköping	October 18, 2019	2006	10	10	1.0	0.92	22	27	0.78	0.67
Ängelholm	October 22, 2019	1979	78	43	0.64	0.46	13	34	0.56	0.30
Uppsala	November 27, 2019	1990	72	47	0.55	0.51	16	20	0.46	0.41
Göteborg	April 12, 2020	—	23	23	0.73	0.35	10	23	0.66	0.27
Göteborg	April 17, 2020	1982	23	23	0.71	0.70	24	4.5	0.54	0.67
Göteborg	June 12, 2020	1987	78	54	0.72	0.54	8,0	10	0.66	0.49
Göteborg	August 3, 2020	1982	67	32	0.71	0.67	46	16	0.38	0.56
Ängelholm	September 17, 2020	1980	68	40	0.23	0.56	25	13	0.17	0.49
Göteborg	April 15, 2021	1981	23	23	0.50	0.25	17	10	0.42	0.22
Stockholm	June 9, 2021	1993	23	—	0.51	—	15		0.43	
Lund	June 29, 2021	1975	70	40	0.34	0.44	16	16	0.29	0.37
Jönköping	June 30, 2021	1983	75	52	0.41	0.56	43	19	0.23	0.45
Jönköping	June 30, 2021	1991	67	42	0.60	0.62	2.8	12	0.58	0.55
Lund	November 19, 2021	1980	23	23	0.67	1.41	7.1	6.4	0.62	1.32

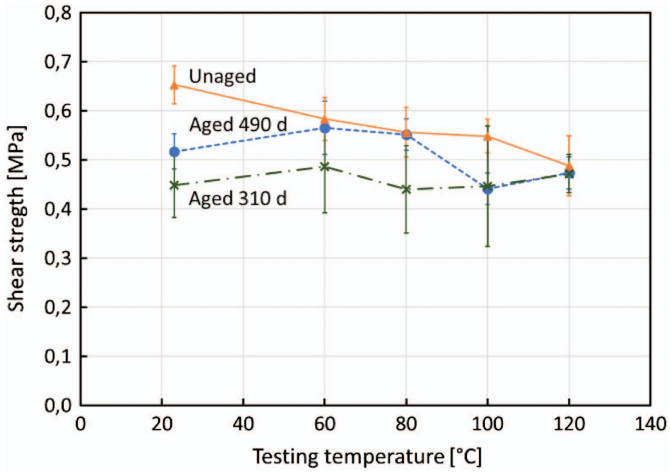

Fig. 4. (Color) Variation in shear strength with temperature measured with the RISE plug method.

The accuracy of the plug method measurement and the correlation with the standard axial shear strength method were examined. Several tests were performed to obtain a correlation between results from the two methods. All tests were performed in the laboratory at 23°C using either naturally aged pipes or pipes after accelerated aging. The measurement of uncertainty includes the variation of the shear strength along the pipe. The uncertainty can be reduced by taking more samples. The results are provided in Table 2.

As seen, the ratio in the shear strength measured with the two methods varies slightly. An average value of the ratio weighted with respect to measurement uncertainty was calculated as 3.1, and an unweighted average gave an equivalent result. Therefore, to estimate a value corresponding to the axial method, a value using the plug method must be divided by 3.1.

FTIR Analysis of Plugs Obtained from the Field Measurements

To determine the degree of chemical degradation, we calculated the relative IR index as a ratio of the IR index from the downside and upside of a plug. A ratio of 1 means that no degradation has taken place, and the lower the value, the more the material close to the service pipe is degraded. The results of IR analyses are shown in Figs. 5 and 6, in which the service time is recalculated using the Arrhenius relationship to the reference temperatures 95 and 55°C for the supply and the return lines, respectively.

The results from the supply pipes (Fig. 5) vary between 1 and 0.4, which suggests that several of the pipes were significantly degraded. The corresponding results from the return pipes (Fig. 6) show a relatively constant high level, as expected, because the operating temperatures in the return pipes are significantly lower and therefore do not lead to measurable degradation of PUR.

Table 2. Comparison between shear strength measured with the plug method and the axial method

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

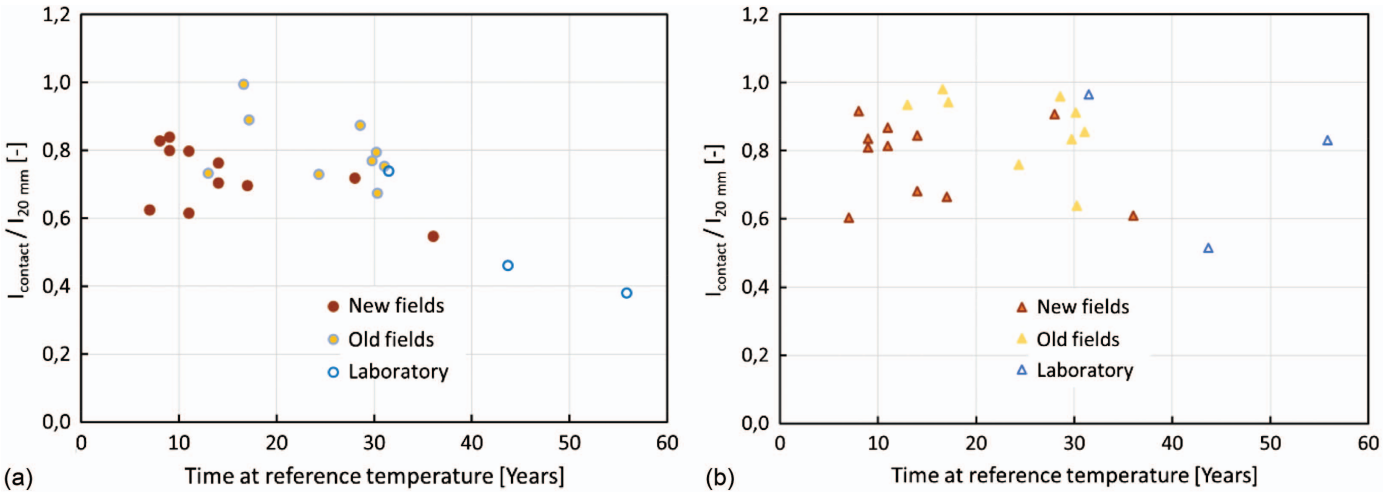

Fig. 5. (Color) Relative IR index for the peak at: (a) 1,712 cm^{-1}; and (b) 1,512 cm^{-1} measured on supply pipes.

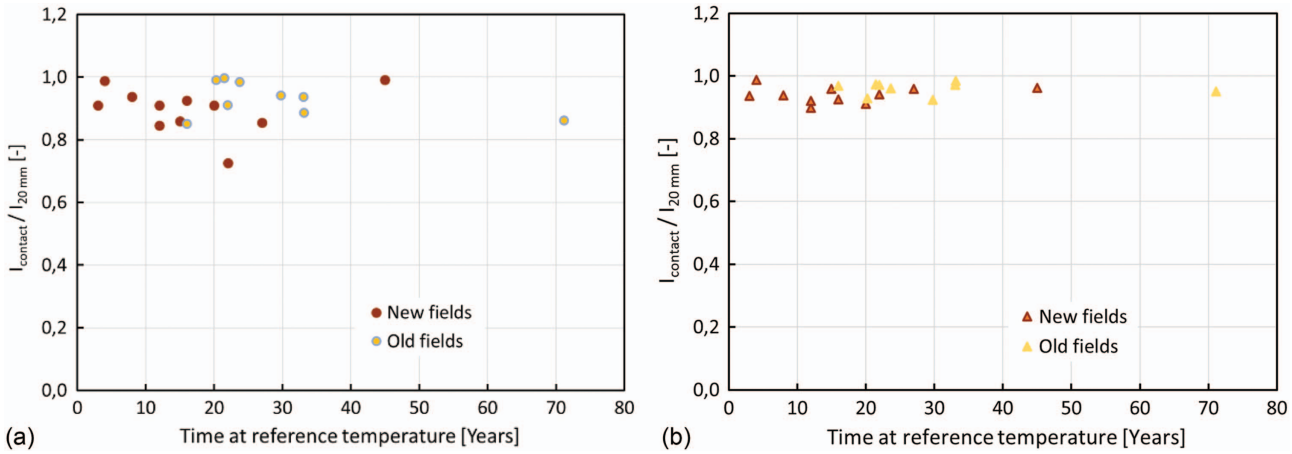

Fig. 6. (Color) Relative IR index for the peak at: (a) 1,712 cm^{-1}; and (b) 1,512 cm^{-1} measured on return pipes.

Restoration of Pipes after Field Testing

The plug method causes only minor damage to the insulation and is like a biopsy on a human body. It is nevertheless very important to restore the pipe after testing to prevent outside water from penetrating the insulation and causing rapid degradation. We therefore developed a restoration method that involves the use of new prefabricated PUR plugs that are pressed into the holes. Then, HDPE round discs are placed on top of the plugs and welded into the casing. Because it is vital that water cannot penetrate the insulation, the restoration method was evaluated by measuring the water tightness of restored pipes.

Water tightness was tested using restored pipes whose ends were carefully sealed with silicone. The pipes were placed in a tank with colored water according to EN 489-1 (CEN 2019a), using the same dyestuff as in DH systems. The pressure was at least a 3-m water column (0.030 MPa) for 24 h. Water tightness was then evaluated by cutting the casing at the plugs for inspection. If water had penetrated the casing, dyestuff would be seen in the foam. An ultraviolet lamp can also be used because the color is fluorescent. Fig. 7 shows the restored pipe after the immersion test in water with fluorescent paint and indicates that no water had penetrated the casing.

Conclusions

Pipeopsy is a unique new field test method proposed to assess the status of old DH pipes in operation. The method consists of three parts: (1) measurement of the adhesion strength between the service pipe and PUR insulation using the plug method, (2) FTIR analysis to evaluate the extent of chemical degradation in PUR, and (3) restoration of the pipeline after testing.

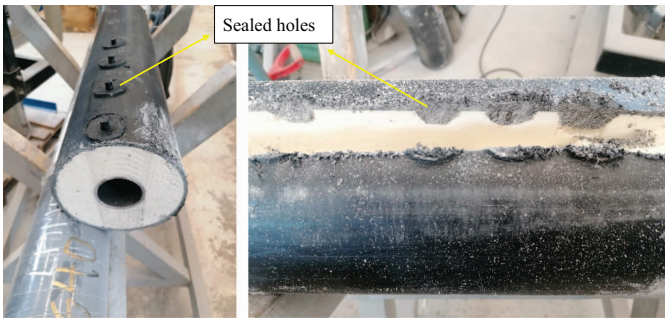

Fig. 7. (Color) Overview of: (a) the restored pipe; and (b) after immersion. The pipe was cut open and inspected for water penetration.

The method provides information on whether adhesion strength between the PUR and the steel is at a satisfactory level. At the same time, FTIR analysis provides information on the degree of degradation of the PUR closest to the steel pipe. If a corresponding investigation can be carried out on a similar return pipe, conclusions can be drawn about how great the reduction in adhesion is and whether it is due to the thermo-oxidative degradation of PUR. With this information, the remaining service life of the DH pipe can be estimated.

The usability of the test method was confirmed in several field tests under real conditions. Field testing often takes place during operation, which means that testing is performed at different temperatures. Therefore, the temperature dependence of the shear strength was examined. It was found that the shear strength of the aged pipes does not show any temperature dependence. Measurement accuracy and the correlation with the standard axial shear strength method was also investigated. Our investigation has shown that to recalculate a result from the plug method to a value from the standard method, it must be divided by a factor of 3.1.

The reason why the plug method can be used while DH lines are in operation is that the test requires only a small portion of the insulation to be removed without damaging the service pipe. It differs significantly from the axial test method, which requires that a certain length of the pipe with all its parts is cut out and removed. To do so, the operation must be stopped so that hot water does not spray out. The proposed method is a novel way to assess the status of old DH pipes in operation. It provides a better basis for decision-makers for prioritization of the maintenance of the 200,000 km of DH pipes in Europe (IEA 2024). The use of the field versions of the axial or tangential shear strength test methods is not viable for status assessment and is rarely used in practice. Pipeopsy, on the other hand, can be used without major limitations in terms of costs and scope of work. Furthermore, the method provides not only information on adhesion strength but also information on the extent of chemical degradation in the PUR. This combination of information provides a more detailed picture of the status of pipes and can be used to make a prediction about the remaining lifetime. Thanks to the proposed method, testing can be performed at a small cost, using simple mobile tools and without shutting down the operation.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published paper.

Acknowledgments

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