Detection of Hydrothermal Aging in Cured-In-Place Pipes (CIPP) Based on Microwave System

Maryam MANAVIPOUR[1], Christoph SKLARCZYK[1], Klaus SZIELASKO[1], Jochen H. KURZ [1], Christian BOLLER [1,2]
[1] Fraunhofer-Institute for Nondestructive Testing, Saarbrücken, Germany

[2] Chair of Nondestructive Testing and Quality Assurance, University of Saarland, Saarbrücken, Germany
Contact e-mail: maryam.manavipour@izfp.fraunhofer.de

Abstract. Pipe rehabilitation by means of trenchless techniques has been performed for more than 40 years already. Cured-in-place pipe (CIPP) is a trenchless method to repair damaged pipelines by inserting a new liner of polymer composite inside the existing host pipe. Since these liners are exposed to water at different temperature after installation for a long time, the purpose of a study was to investigate the effect of hydrothermal aging on CIPP samples and how this effect can be assessed by means of nondestructive testing.
The hydrothermal aging was performed by immersion of liner samples in double-distilled water at 65°C. The effect of aging on the samples was determined by comparison of reference information (optical microscopy images and weight) with nondestructive testing parameters using microwaves. For nondestructive material testing, microwaves have been applied in the frequency range between 0.3 and 300 GHz. Microwave based methods have the advantage of no direct coupling between the probe and the object under test being required, such that the evaluation can be performed remotely from a standoff distance. The microwaves used in this study were in the frequency range of 75 - 100 GHz. For this a vector network analyzer (VNA) with frequency-modulated continuous wave (FMCW) radar was used to enable an accurate and broadband measurement.
The effect of water-induced aging appeared as a change in the received microwave amplitude, which results from a change in permittivity of the material being inspected. The results of the weight measurement proved the water absorption in the samples. Moreover, the effects of water absorption were visible in the optic microscopic images as cracks and de-bonding between fibers and matrix. Getting those results combined does result in an approach on how to hopefully assess CIPP liners in service in the future.

1. Introduction

1.1. CIPP Liners

A liner is one of the trenchless reconditioning methods that allow the renewal of buried water and waste water pipes without full excavation from the ground surface, but rather through existing manholes or other entry points [1,2].

In the context of quality assurance of CIPP, the degradation of the materials after installation and also after some years of operation is inevitable [3]. This degradation consists of changing thickness, deterioration of mechanical properties, leakage, cracks, changing appearance and many more which accrues after about 10 years.

Up to now all of these properties are characterized by means of destructive methods. Using closed-circuit television cameras is an exception, which enables observing the surface of liners and its changes.

The aim of this paper is to demonstrate NDT options in terms of microwave and optic microscopy methods for characterizing liner properties after hydrothermal aging. In the case to accelerate the hydrothermal aging, we used 65°C, but higher temperature is not allowed because as it cannot occur normally in wastewater and higher temperature may have other effects on properties on material.

1.2. Theory of Microwave Testing

Like with all electromagnetic radiation, microwave propagation depends on the interaction between time-varying electric and magnetic fields. These fields oscillate in waves that are called travelling waves because energy is transported from one position to another. According to the medium through which the electromagnetic waves propagate, the velocity of propagation changes. Microwaves lie within a broad frequency range from 300 MHz up to 300 GHz, corresponding to wavelengths of 100 – 0.1 cm. Electromagnetic microwave radiation has been used in the determination of water content in various materials for at least four decades. One of the most important applications of microwave sensors is measurement of moisture.

The propagation of a plane electromagnetic wave along the x-axis in a lossy medium that can be described by

$$\overline{E} = \overline{E}_0 \exp(-jkx) \tag{1}$$

where $\overline{E}$: Electric field strength and $\overline{E}_0$: peak value (vector) of $\overline{E}$, while

$$k = k' - jk'' \tag{2}$$

K is the complex propagation factor, where k' is the real part and k'' is the loss factor by which the propagation losses in the medium are taken into account.

Dielectric spectroscopy determines the dielectric properties of the sample as a function of frequency. The complex permittivity ε is the dielectric property that describes how the material under an electromagnetic field influences the electric field.

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{3}$$

where ε' is the absolute permittivity or real part of permittivity and ε'' is the absolute loss factor or imaginary part of permittivity [4].

Absolute permittivity reflects a material's ability to store energy, and the loss factor is related to the absorption and dissipation of the electromagnetic energy by conversion into other kinds of energy (such as the thermal kind). The propagation factor is related to the permittivity by

$$k = 2\pi f \sqrt{\mu\varepsilon} \tag{4}$$

also

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \tag{5}$$

where μ is the magnetic permeability and c is the propagation speed.

The values for permittivity, permeability and speed of propagation in vacuum are:

$$\varepsilon_0 = 8.854 \times 10^{-12}\ F/m$$

$$\mu_0 = 4\pi \times 10^{-7}\ H/m$$

$$c_0 = 2.998 \times 10^{8}\ m/s$$

In any medium other than vacuum, the constants obtain higher values and are usually expressed relative to the values in vacuum:

$$\varepsilon = \varepsilon_r \varepsilon_0 \quad (6)$$

$$\mu = \mu_r \mu_0 \quad (7)$$

where the subscript "r" stands for "relative". For para-/diamagnetic materials, $\mu_r \approx 1$. Therefore [5]:

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \approx \frac{c_0}{\sqrt{\varepsilon_r'}} \quad (8)$$

The reflection coefficient of electromagnetic waves at an interface is given by:

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon}_1 + \sqrt{\varepsilon_2}} \quad (9)$$

where

ε_1: Permittivity of the first medium, e.g. air

ε_2: Permittivity of the 2nd medium, e.g. specimen [6].

In the microwave range, free (i.e. chemically non-bonded) water exhibits a much higher permittivity (both real and imaginary part) than most solid materials [5]. Therefore, by adding water to the solid, its moisture is increased, resulting in a substantial effect on permittivity. This difference in permittivity can be detected by microwave sensors. Therefore a change in permittivity will affect the velocity and attenuation of microwaves in material, as can be seen from equation 5.

2. Material

The material studied was unsaturated polyester reinforced with unwoven polyethylene terephthalate (PET) fibers. The resin is the classical isophthalic-based polyester resin (Ortho Neopentyl glycol resins (O-NPG)), with primary catalyst Perkadox 0.8% and secondary catalyst Triganox 1.0% and 40% aluminum trihydrate as filler. PET fibers with a density of 1.45 g/cm^3 and a melting point about 252 °C were used. PET is a thermoplastic polymer, formed by polycondensation reaction between terephthalic acid and ethylene glycol, which may exist as amorphous and semi-crystalline material.

Table 1: Physical and mechanical properties of fibers and matrix

Materials	Flexural E-Modulus (GPa)	Flexural strength (MPa)	Sealed	Thickness (mm)	Glass transition temperature T_g (°C)	Fiber volume fraction	Density (gr/ml)	Profile
UP/PET	3.247	32	yes	19.2	122	25%	1.31	DN 1000

3. Experimental methods

Hydrothermal aging:

3 specimens were cut into plates with dimension of approximately 20 mm x 20 mm x 20 mm. The samples were dried in an oven for 1 hour at 108±3 °C, allowed to cool down in a desiccator, and immediately weighed with an electronic weighing scale with 10^{-4} g readability. This weight refers to conditioned weight (W_0). The weight was also measured along the aging process.

The samples were then immersed in distilled water after preheating and stored in an oven at 65 °C. After 24 hours the specimens were removed from the water, gently wiped free from surface moisture with a dry cloth, and weighed immediately (W_W). The weighing was repeated at the end of the first week and every two weeks thereafter until the increase in weight per two-week period by three descending consecutive weighing reached less than 0.02%. The specimens were then considered substantially saturated. The samples were dried again in an oven for 1 hour at 108±3 °C and cooled down in a desiccator.

$$\%\,increase\ in\ weight\,(M_a) = \frac{W_w - W_0}{W_0} \times 100 \qquad (10)$$

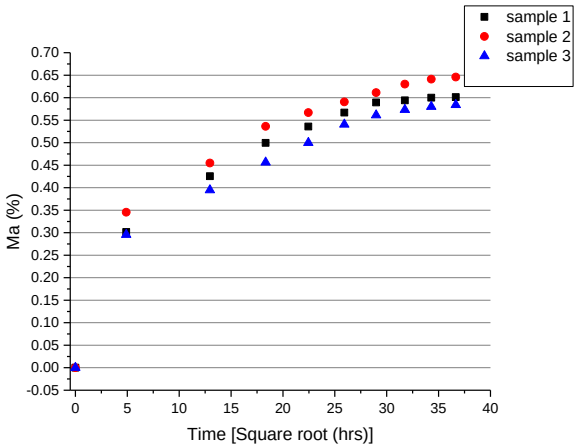


Figure 1: Weight gain curves at 65°C of 3 CIPP specimens

The water absorption ability of 3 samples can be seen in Figure 1 according to the Equation (10) [7]. The mass uptake apparently ceases at 0.6%.
The weight-change behavior of the randomly orientated fiber/unsaturated polyester was evaluated by the weight gain due to the water absorption in the matrix, fiber and their interface.
The microstructures were examined using a Leica DM600 optical microscope before and after hydrothermal aging.
The microscopic observations explain the interphase damage mechanisms and especially the irreversible damage process. Water absorption reduces the fiber/matrix adhesion by, for example dissolution of the coupling agent [8] thus leading to interfacial debonding.
The samples were characterized with time domain microwave reflectometry (75 – 100 GHz) before aging and immediately after aging. After that the samples were placed in an oven for 1 hour and allowed to cool down in a desiccator, before they were characterized with microwaves once more.

4. Results and discussion

As a result of water diffusion, debonding at the fiber/matrix interface occurred; therefore the binder dissolved easily into water through the interface [7].
Two types of degradation are distinguished in Figure 2:

1. Matrix osmotic cracking
2. Interfacial debonding

Both may be induced by differential swelling or by osmotic cracking at the interphase. In fact the interfacial zone constitutes of a suitable site for osmosis processes because of stress concentration and fiber substance leaching.

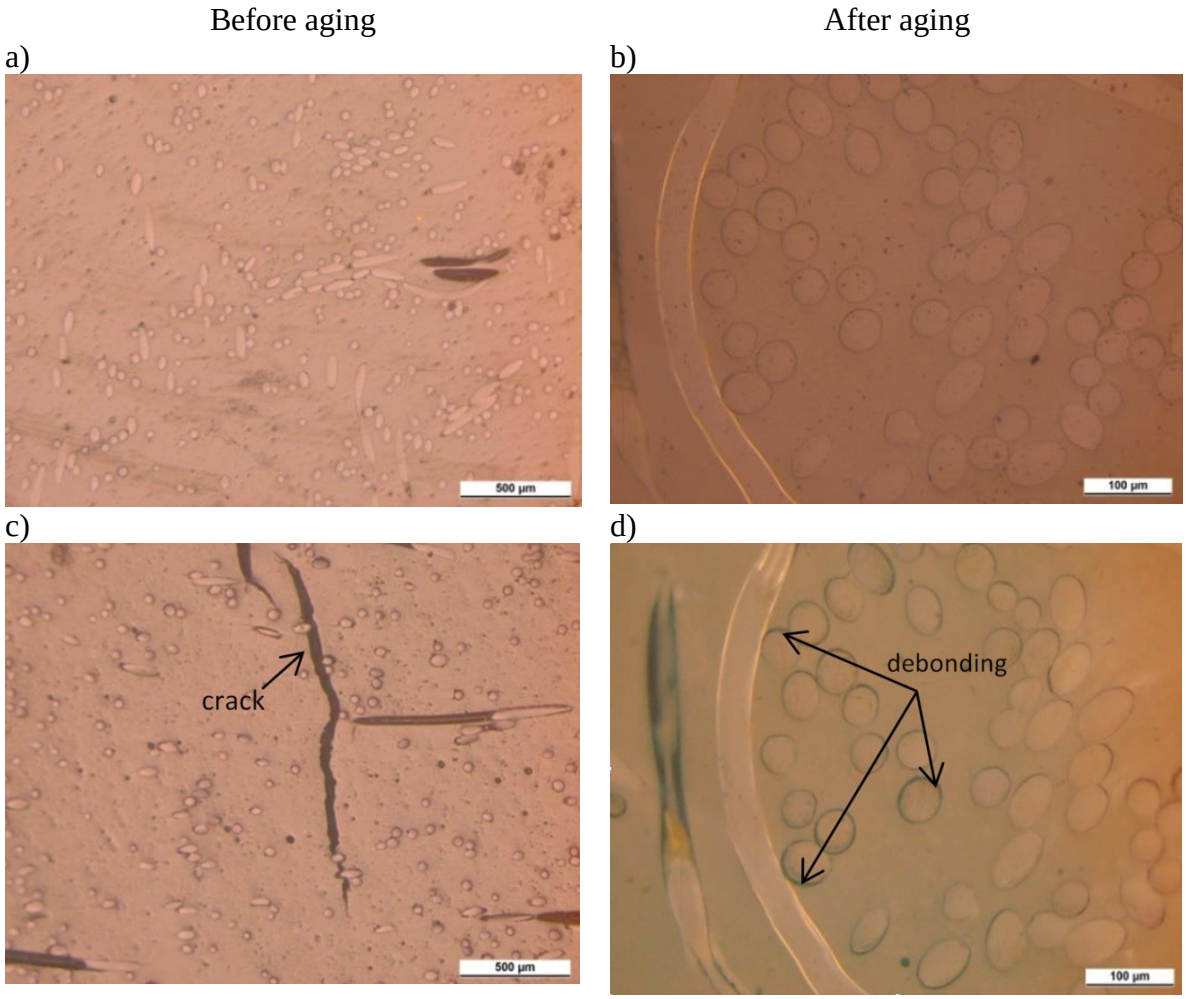


Figure 2: Optical microscopic observation. a,b) before aging. c) Matrix osmotic cracking after aging and d) Interfacial debonding after aging

To explain the degradation of the liner, the material and the curing process need to be investigated. Styrene is added in order to accelerate the curing process. It acts as a solvent [9] which creates cross-linking units by reacting with the unsaturated resin.
In the case that the polymers are incompletely polymerized, low heat stability, low resistance to hydrolysis and greater degree of swelling would appear. Aging in water promotes further reaction of the residual styrene monomer and an increase in glass transition temperature (T_g). Weight loss of polymers during water immersion has the same trend, as it is related to the leach-out of some of the components or portions of the macromolecular segments initially present in the resin [10].

The cured isophthalic polyester used in this research has $T_g = 122$ °C. The hydrolysis behavior is highly dependent on the temperature. The higher the temperature and the nearer it is to T_g, the higher the possibility of hydrolysis. In this paper we used 65 °C, since the liners are not exposed to higher temperature in wastewater canals. Hence, hydrolysis effects and weight loss during water absorption cannot be observed here. The only irreversible phenomenon that can occur as a result of hydrothermal ageing is osmotic cracking and debonding. An increased temperature causes higher water uptake. This may be explained by crack appearance or by water accumulation at the fiber/matrix interface [11]. The weight loss due to dissolution of the coupling agent is negligible in comparison to water uptake. Therefore no weight loss is observed in Figure 1.

Existence of water molecules in the material changes the permittivity and permeability. Since the variation in the permeability is negligible in this study, and since the specimens are dielectric materials, we assume that permeability $\mu=1$.

The speed of microwaves in a CIPP specimen can be calculated by knowing the thickness x of the specimen and the time of flight Δt.

$$c = \frac{x}{\Delta t} \tag{11}$$

Assuming that the speed of microwave propagation in vacuum is:

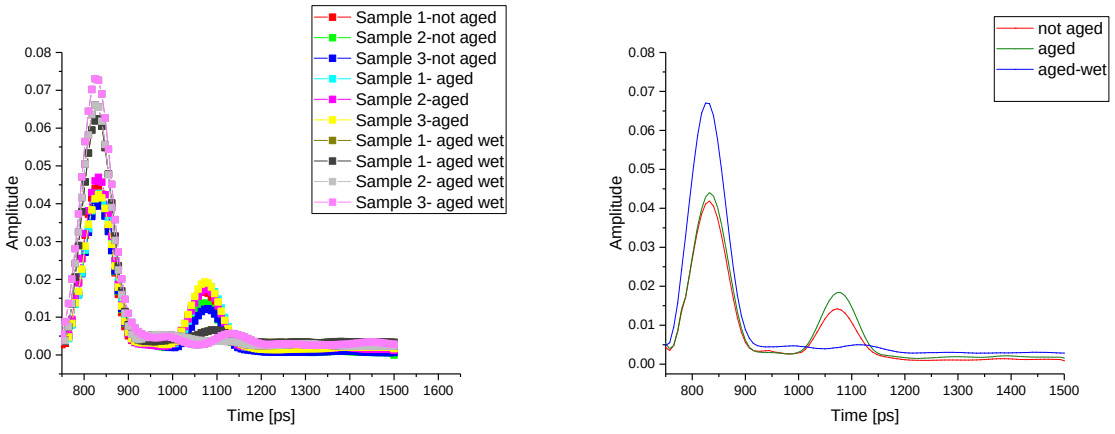
$c_0 = 2.998 \times 10^8 \, m/s$

then ε_r' can be determined from Equation *8*.

A time domain measurement reveals the effects of all individual discontinuities due to permittivity changes, as a function of time (or distance). Here, a discontinuity means a change of medium.

Figure 3(a) shows the time-domain reflectometry signal of 3 specimens before aging and after aging once moist and once after drying in oven. Each signal represents an average of 20 measurements of every sample. Every signal contains 2 peaks which belong to the interface between air and specimen, and vice versa. The first peak refers to the front wall and the second one to the back wall of the specimen. Figure 3b shows the average of 3 samples in every aging condition.

By adding free water to the dry CIPP specimen ("aged-wet" condition), the imaginary part of permittivity is increased, resulting in a decrease of the back wall echo amplitude. The amplitude of the peak of the front wall shows the difference of permittivity between air and specimen. An increase in the front wall echo amplitude is related to the increase of permittivity because of water absorption. It is observed that after drying the specimens (condition "aged"), the front wall echo is almost the same as for non-aged samples, but the echo of the back wall is higher in comparison to the condition before aging. It can be assumed that dissolving the coupling agent during the aging process made the specimen more homogenous. Therefore the microwave signal was not scattered as much as before due to non-uniformities in the medium, leading to decreased absorption and higher back-wall echo. With having the echo of front wall and back wall, the time of flight is calculable (Figure 3). When we know the permittivity of the liner the speed of microwaves is calculable (Equation 8). From Equation 11 it is possible to measure the thickness of the specimen. It means that it is possible to measure the thickness of the liner also in situ without cutting off a piece of it. The only point is that the liner should not be wet. Since one of the noticeable problems of a liner is its reduction in thickness, this method helps us to detect the area of the liner where a thickness is unacceptable.



a) b)

Figure 3: Reflection measurement in time domain mode of 3 specimens before aging, immediately after aging and after aging dried (a). The average of signals of 3 samples in 3 different conditions (b). The values are displayed in arbitrary units.

5. Conclusions

In this article a microwave-based technique has been used to detect the effect of hydrothermal aging in CIPP specimens. This experiment was performed to show the changing of the weight and morphology of liner specimens due to 8 weeks of water immersion at 65°C. The effects of aging have clearly been observed in optic microscope images. The water absorption led to matrix cracking and interface debonding.
The microwave measurements revealed the sensitivity of the complex permittivity to water absorption in the CIPP specimens. Increase in water content significantly increased attenuation, which refers to an increase in the imaginary part of permittivity. It was observed that the thickness of the CIPP is by microwaves before and after aging measurable, when the liners are in dry condition. Up to now the only possibility to measure the thickness was cutting a piece of liner and measuring it in laboratory by caliper.

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