The Effect of Water Aging on Cured-In-Place Pipe (CIPP) Samples Using Non-Destructive Tests

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Abstract
Pipe rehabilitation and trenchless pipe replacement technologies have been used more than 40 years. Cured-in-place pipe (CIPP) is a trenchless method to repair damaged pipelines by inserting a new liner of polymer inside the existing host pipe.
Since these liners are exposed to water after installation, the purpose of this study is to investigate the effect of water aging on CIPP samples. The water absorption analyses have been performed by immersion of unsaturated polyester composites reinforced with needle felt samples in distilled water according to ASTM D570/98. The effect of aging is inspected on one hand via comparison of their images obtained through an optic microscope and their weights before and after aging and on the other hand through non-destructive testing using microwaves. The microwaves were used in the frequency range of 75 - 100 GHz in non-contact manner. For this a vectorial network analyser (VNWA) and a frequency-modulated continuous wave radar (FMCW radar) was used to enable an accurate and broadband measurement.
In this case the effect of water induced aging appears as a change in run time, which results from a change in permittivity of the material being inspected. The results of the optic microscopic images and weights prove that water absorption is present in the CIPP samples considered.

Keywords: Microwave, cured-in-place pipe (CIPP), water aging, unsaturated polyester, needle felt composite

1. Introduction

Around 40 years have passed since development and introduction of the trenchless sewer pipe rehabilitation method of cured-in-place pipe (CIPP). The host pipes, which are partially deteriorated, are rehabilitated through a polymeric liner. Trenchless methods are frequently used to rehabilitate or replace deteriorated sewer mains, seal leaky joints and cracks and to repair service laterals. They are mainly thermosetting polymers, which are inserted into the host pipe by pulled in place installation or by inverting the resin-impregnated flexible tube under water or air pressure [1].
In association with quality assurance of the CIPP [2], the degradation of the materials after installation and also after some years of operation is unavoidable. Therefore, inspection procedures, which are fast, automatable and do not require manual measurements, are required [3]. The principle of detecting the effect of water aging in CIPP structures will be demonstrated subsequently.
One of the most important applications of microwave sensors is measurement of moisture. Microwaves lie within a broad frequency range of electromagnetic waves, from 300 MHz up

to 300 GHz with wavelengths of 100 – 0.1 cm. Microwave electromagnetic radiation has been used in the determination of water content in various materials for at least four decades.
The propagation of a plane electromagnetic wave along the x-axis in a lossy medium 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' refers to as the absolute permittivity or real part of permittivity and ε'' refers to as the absolute loss factor or imaginary part of permittivity [4]. The absolute permittivity is related to the materials' ability to store energy and the loss factor is related to the absorption and dissipation of the electromagnetic energy in other kinds of energy such as the thermal. 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 medium, other than a vacuum, the constants obtain higher values and are usually expressed relative to the values in vacuum:

$$\varepsilon = \varepsilon_r \varepsilon_0 \tag{6}$$

$$\mu = \mu_r \mu_0 \tag{7}$$

where the subscript r stands for "relative". For nonmagnetic materials, $\mu_r = 1$. Therefore [5]:

$$c = \frac{1}{\sqrt{\mu\varepsilon}} \approx \frac{c_0}{\sqrt{\varepsilon_r^{'}}} \tag{8}$$

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

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \tag{9}$$

Where

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

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

In 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. Materials and methods

The following section described the samples used and the methods considered to investigate the effect of water aging on the CIPP specimens.

2.1. CIPP sample: The sample used was made of unsaturated polyester resin reinforced by polyester synthesis fibres. Figure 1 shows the CIPP sample removed from CIPP tube. Two specimens were cut in size 2.7 cm × 2.9 cm.

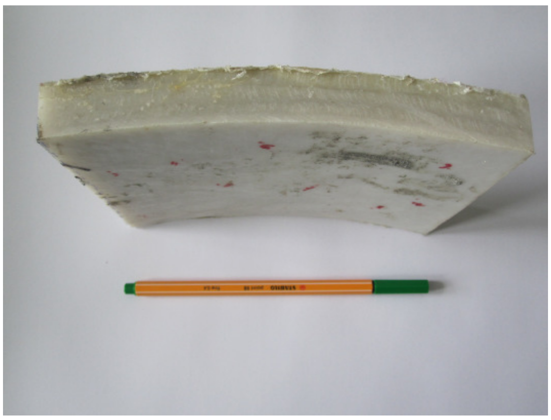

Figure 1. CIPP specimen taken out from a tube

Table 1 provides the details of the sample.

Table 1. specimen characterization

Resin	Unsaturated polyester resin
Fibre	Polyester synthesis fibre
Profile	DN* 1000
Liner thickness [mm]	19.20
Installation	Inversion
E-Modulus [GPa]**	3.247
3 point flexural stress [MPa]**	32
Leakage test***	sealed

* Diameter nominal
** According to DIN EN ISO 178 [7] and DIN EN 13566-4 [8]
*** According to DIN EN 1610 [9]

2.2. Sample preparation: In order to use optic microscopy, the surface of the samples should be ground and polished. We call the sample 13.0596 g and 13.5145 g respectively as specimen 1 and specimen 2. The microstructures were examined using a Leica DM600 optic microscope. The length of fibres was measured to compare before and after aging.

2.3. VNWA: In order to obtain a high spatial resolutions signal from the CIPP, microwaves have been applied in the frequency range of millimetre waves between 75 GHz und 100 GHz, corresponding to a wavelength in vacuum of 4 to 3 mm in a non-contact manner (free space) in the reflection mode and with time domain mode.
For this purpose, a vector network analyser system (VNWA) was used which allows an accurate and wide-band measurement. The test system allows the measurement of phase and amplitude as well as real and imaginary parts. A horn antenna (aperture about 6×9 mm²) was used both as a transmitting and as a receiving antenna. It transmits the microwaves perpendicular to the inside surface of CIPP. The distance between the sample and end of the antenna was 50 mm. The scattering parameter S_{11} has been detected at each measurement position for 201 frequencies between 75 GHz and 100 GHz.

a b

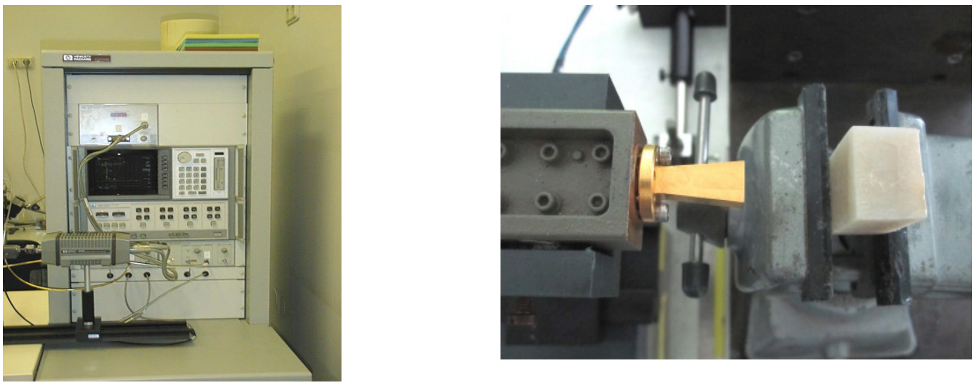

Figure 2. (a) Vector network analyzer with amplifiers and source module. (b) horn antenna and sample with 50 mm distance

2.4. Weighing: The samples were dried in an oven for 1 hour at 108 +/- 3 °C, cooled in a desiccator, and immediately weighed with an electronic weighing scale with 10^{-4} g readability. This weight refers to conditioned weight. The weight was also measured along the aging process.

2.5. Water aging: The water aging process applied has been according to ASTM D570/98 [10]. The samples were immersed in distilled water after preheating and weighing at room temperature. After 24 hours the specimens were removed from the water, wiped free of surface moisture with a dry cloth, and weighed immediately. The weighing has been repeated at the end of the first week and every two weeks thereafter until the increase in weight per two-week period by three consecutive weighings, average less than 1% of the total increase in weight or 5 mg, whichever is greater. The specimen shall then be considered substantially saturated. The increase in weight during immersion has been calculated as follows:

$$\%increase\ in\ weight = \frac{wet\ weight - conditioned\ weight}{conditioned\ weight} \times 100 \tag{10}$$

3. Results and discussion

Figure 3 shows that after 5 weeks (840 hours) of immersion in distilled water, the average increase in weight of the specimens showed 3 times less than 1% and 5 mg increase in weight, therefore it has been assumed to be saturated.

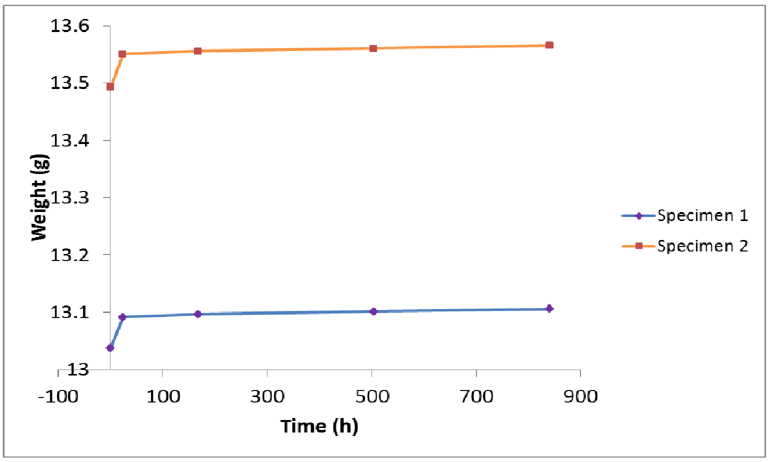

Figure 3. Process of saturation

From equation *10*, the increases of weights were calculated to be 0.52% for specimen 1 and 0.54% for specimen 2 after 5 weeks.

Figure 4 presents the effect of water absorption in the specimens. Microscopic images before and after aging show the observable extension in the length of the polyester synthesis fibres.

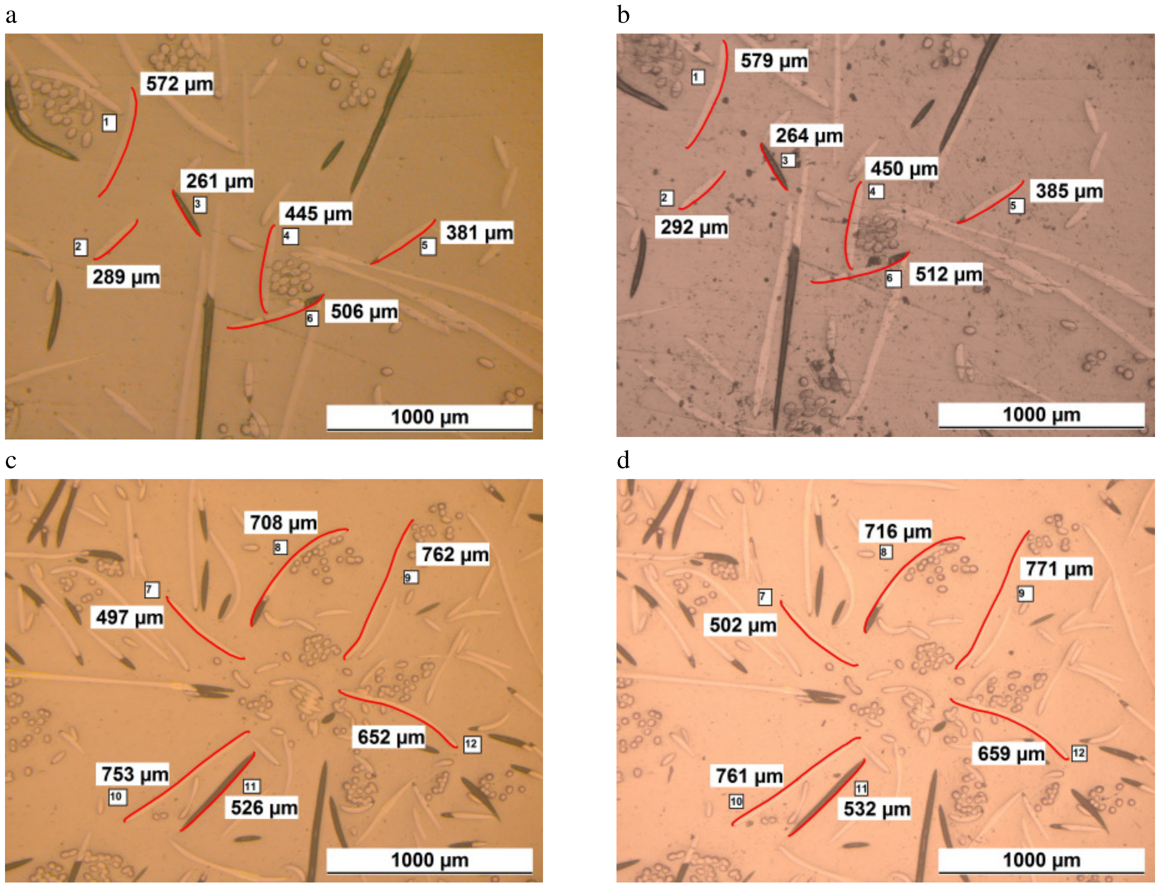

Figure 4. Optic microscopic images of CIPP samples showing surface morphology (a) specimen 1 before aging (b) specimen 1after 5 weeks aging (c) specimen 2 before aging (d) specimen 2 after 5 weeks aging

We can measure the %increase length of the 12 marked fibres before and after aging in 2 specimens with equation *11*:

$$\%increase\ in\ length = \frac{length\ after\ aging - length\ before\ aging}{length\ before\ aging} \times 100 \quad (11)$$

Figure 5 shows the %increase length of different fibres from 1.03% to 1.41%.

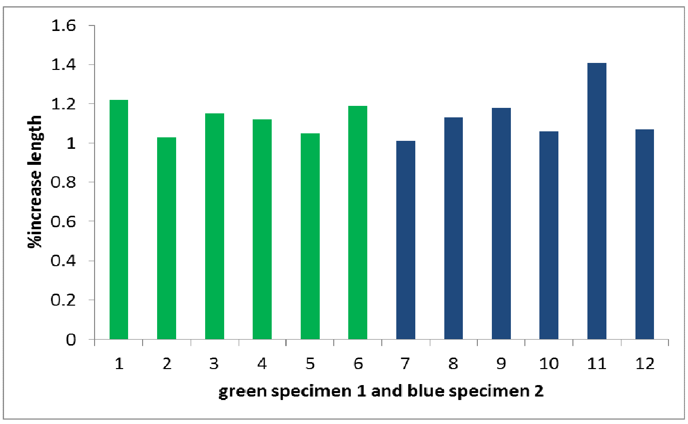

Figure 5. the %increase length of different fibres specimen 1 and 2

Presence of water molecules in the material changes the permittivity and permeability. Considering the fact that the variation in the permeability is negligible in this study, and since the specimens are dielectric materials, we assume that permeability μ=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 Δ*t*.

$$c = \frac{x}{\Delta t} \tag{12}$$

If we assume the speed of microwave propagation in vacuum to be

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

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

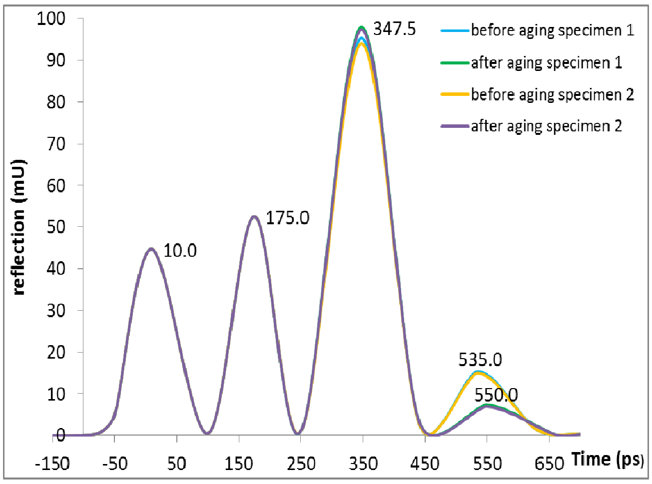

Figure 6. Reflection measurement in time domain mode of specimen 1 and 2. The values are displayed in relative units (U: units; mU: milliunits).

As explained before in section 2, a time domain measurement provides the effects of all individual discontinuities due to the permittivity changes, as a function of time (or distance). Discontinuity means, where the medium changes.
Figure 6 shows the signal of specimen 1 and 2. The signals for two specimens along time axis had the same amplitude and overlapped and along the reflection axis, the difference is too few, that it is hard to distinguish the signals. Every signal contains 4 peaks where each peak belongs to the interface between air and specimen or antenna and vice versa. The 2 first peaks belong to the beginning and the end of the antenna and the 2 last peaks are given by the front wall and the back wall of the specimen (see Figure 2 (b)).
In Figure 6, one can observe that the microwave signal needed more time to pass through the specimen after aging. There are two reasons for this. One is due to swelling of the specimen after water absorption. Swelling increases the thickness, which through it the waves pass. The second reason is related to the rise of the permittivity after aging. In order to show that the increase in time of flight is more than the time, which is required to pass through the enlarged thickness and hence encompasses also the rise in permittivity, we considered the both parameters, time and thickness by measuring the velocity.

Table 2 shows the variation in the real part of permittivity and the velocity of microwaves in abraded and polished CIPP. In the dry material ε_r'' is too small to be measurable and can be estimated as << 1 [5].

Table 2. CIPP characterization before and after aging

	before aging Specimen 1	after aging Specimen 1	before aging Specimen 2	after aging Specimen 2
Weight (g)	13.0382 (Conditioned weight)	13.1060	13.4925 (Conditioned weight)	13.5651
Thickness (mm)	16.02	16.20	16.14	16.33
Time of flight (ps)	180.0	202.5	180.0	202.5
c (m/s)×10^8	1.780	1.600	1.793	1.613
ε_r'	2.84	3.51	2.80	3.45

Water exhibits a much higher permittivity (real and imaginary part of equation *3*) than the dry substrate [5]. According to Nyfors and Vainikainen [5] in the frequency range as used in this investigation the permittivity of pure water lies between $\varepsilon_r = 8.4 - j15.9$ for 75 GHz and $\varepsilon_r = 6.9 - j12.2$ for 100 GHz while the permittivity of the dry CIPP material is much lower (see Table 2). From table 2, the increase of the permittivity can be 23% calculated.
By adding free water to the dry CIPP specimen, according to the mixing rules as given e.g. by Nyfors and Vainikainen [5] both real and imaginary part of permittivity is increased resulting in an increase of the reflection coefficient (peak 3 in Figure 6) according to equation *9* and an increase of absorption inside the material according to equation *2* and *3*. Considerable absorption can be seen in decreasing of the back wall echo (peak 4 in Figure 6). Furthermore some temporal shift of peak 4 to the right direction can be found which is due to the increased permittivity and thus decreased propagation speed (see equation *5*) in the moist material compared to the dry material.
With the help of table 2 calculation of %increase of the thickness is possible. It is calculated for specimen 1 as 1.12% and for specimen 2 as 1.18%. This range contains the extension of fibres elongation with the average of 1.135% (Figure 5).

4. Conclusions

In this article a microwave based technique has been used to detect the effect of water aging a CIPP specimen considering time of flight of the microwaves. This experiment was performed to show the increase of the weight and thickness of a specimen due to a 5 weeks' immersion time. The effect of aging has been clearly observed from the optic microscope images. The water absorption could be observed by growth in size of the fibres, which has the range of thickness elongation.
The microwave attenuation and time shift measurements showed sensitivity of the complex permittivity with water absorption in the CIPP specimen. Increase in water content significantly increased both time of flight and attenuation. The former refers to an increase in the real part of permittivity and the latter indicates an increase in the imaginary part of permittivity.

5. Acknowledgments

This work is financially supported by Fraunhofer Institute for Nondestructive Testing Saarbrücken. The authors would like to express their gratitude to Mr. Matthias Goebel for his technical support.

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