Physical Ageing of uPVC Gas and Water Pipes

Frans Scholten (frans.scholten@kiwa.nl) and Mannes Wolters
Kiwa Gas Technology BV, PO Box 137, 7300 AC, Apeldoorn, The Netherlands.

Abstract

The kinetics of physical ageing of un-plasticized PVC was investigated using Differential Scanning Calorimetry. A quantitative model was set up that describes the influence of ageing time and temperature on the well-known endothermic ageing peak. The activation energy for physical ageing of 116 kJoule/mole is very close to the literature value (115 kJoule/mole). Physical ageing of uPVC pipes leads to a decrease in impact resistance and may – for uPVC water pipes – decrease the water hammer resistance. To study this, Rapid Crack Propagation measurements were performed, to assess the Critical Pressure. Crack initiation was always performed where the wall was at its thickest. Thus, RCP data was obtained with about 80% less scatter than usual.
Excavated uPVC gas and water pipes have absorbed varying concentrations of water (maximum uptake 0.6 %) and carbon dioxide, which both act as plasticizer. Along with physical ageing these phenomena may affect impact performance.

Introduction

The main question for owners of un-plasticized PVC (uPVC) grids for gas and water distribution is how to evaluate the remaining quality of old pipelines. To answer this question it must be known:

- which changes PVC pipeline materials undergo during service
- what the important failure mechanisms are when these pipelines approach their intended lifetime of 50 years

Some PVC gas grids are nearing or have already passed the originally intended lifetime of 50 years. Still failures of PVC gas pipes are still rare. The 22,500 km of installed gas pipe length in The Netherlands still represents a considerable economical value. Replacement would add costs for installation and road repair. SDR41 uPVC water pipes are used in the Netherlands at pressures up to 6 bars. Here also, not many failures are noted.

It is well-known that amorphous polymers such as PVC are subject to physical ageing. Hutchinson [1] provides an excellent overview and Berens and Hodge [2] present DSC results. One of the goals of the present contribution is to derive a mathematical model to describe the rate of physical ageing. The model was extended by more data at 35 °C than previously available [3]. In future this model will be used to assess the extent of physical ageing in old PVC pipes and support determining its influence on the mechanical properties.
The extent of physical ageing increases by both an increasing ageing temperature and longer ageing times [1, 2, 3]. The time that has elapsed since installation of old PVC pipes is often relatively well known. However, the exact temperature profile the pipe has experienced is much more difficult to assess.
In practice, two temperature regions exist sequentially. Pipe temperatures may be appreciably above 20 °C during storage before installation, at either the extruder's premises or on the installation site, as a result of heating by the sun. This may lead to physical ageing as well as UV oxidation. Next, the pipes are at temperatures below 20 °C during most of their

underground use. In this phase ageing will be slow, but the ageing time is long.
If mechanical tests are performed on excavated pipes, it is important to realise that higher temperatures may again be reached during outside storage after excavation. The extent of ageing may influence several mechanical properties. Ageing leads to an increase of the upper yield strength [1, 4] but to a reduction of the impact resistance [5, 6].
Next, the most important failure mechanisms of old pipelines are discussed.

uPVC gas pipes have been installed in distribution grids in the Netherlands since 1955. After 1975, only impact-modified PVC gas pipes were installed, but in this contribution the focus is on uPVC pipes. The maximum gas pressure Dutch uPVC and impact-modified PVC gas pipes are exposed to is 200 mbar. This is so far below the load bearing capacity of PVC pipes, that internal water pressure testing and tensile testing are not the most adequate methods for assessing the residual lifetime of PVC gas distribution pipes. So for gas pipes impact testing is more important, especially in view of any digging work performed at or near pipelines by owners or third parties.
Hermkens et al [7] have published tensile impact resistance data of excavated PVC gas pipes. The average impact energy they found was 126 kJoule/m^2 and the standard deviation was 26 kJoule/m^2. Both this standard deviation and the scatter in the results within one pipe are relatively high. The reasons for this are not yet clear.

For PVC water pipes impact resistance is important as well. For such pipes, a failure mechanism not very well known is Rapid Crack Propagation (RCP), although results are published [8]. In recent years, such a failure mechanism was occasionally noted in practice. These findings have led the authors to investigate RCP in water pipes, using the S4 test. Because of the wall thickness variations over the pipe circumference, it was decided to always initiate the crack at the position along the circumference with the thickest part of the wall.

Other phenomena occurring during service are important as well. Excavated PVC pipes often contain a low content of water and carbon dioxide gas. PVC is not well-known for absorbing these components from its environment. Both water and carbon dioxide act as plasticizer in PVC [9, 10] and variable contents of these substances may lead to additional scatter in the impact test results of the gas pipes and the RCP results of the water pipes. Therefore, water and carbon dioxide contents were studied using FTIR spectroscopy and weight change measurements.

Materials and Methods

For the ageing studies the investigated pipe segments were taken from the Dutch uPVC gas distribution grid, which had been in use for about 30 to 50 years. The dichloromethane-temperature test according to ISO 9852, but modified by using three different temperatures (5, 10 and 15 °C), was used to assess under-gelation, optimum gelation and over-gelation. Pipe 6-009 had an optimum degree of gelation and pipe 6-023 was over-gelled (both 110 mm).
To study water and carbon dioxide content, pipe samples from the Dutch gas distribution grids were used, but a Dutch water distribution pipe and a German gas distribution pipe were investigated as well. The pipe diameter ranged from 50 to 160 mm.
For the S4 tests unused 315 mm uPVC SDR41 water pipes produced in 2010 by a Dutch pipe manufacturer were tested.

DSC analyses were performed using a Perkin Elmer DSC 7 instrument flushed with pure nitrogen. The instrument was calibrated using very pure indium and tin, to an accuracy better

than ± 0.1 °C. The heating rate was 20 °C/minute. A second heating experiment on the same DSC sample was always used in the ageing studies. The sample is rejuvenated by the first heating experiment to 220 °C, which brings it far above the glass transition temperature. To avoid an increase in crystallinity [3] during slow cooling the cooling rate after the first heating in the DSC was as high as possible, 400 °C/minute nominally.

Foil samples with a thickness between 25 and 100 microns were cut from the pipes for FTIR transmission spectroscopy using a Biorad FTS 3000MX spectrometer.

For water content analysis, a thin foil was cut, water-saturated by submersion in water, dried with paper tissue to remove adhering liquid water and weighted. Next, the sample was placed in a desiccator containing silica gel at the bottom and its weight and spectrum measured after different time intervals, up to complete dryness, each time after wiping with paper tissue.

The S4 tests on the unused 315 mm uPVC pipes were performed according to ISO 13477. Some additional precautions not mentioned in this standard were taken. The most important one was that before the S4 test, the wall thickness at 12 locations equally divided along the circumference of the pipes was measured. All pipes showed wall thickness variations (reported below), although always within the limits required by the PVC Water Pipe Standard (ISO 1452-2:2009). Next, the location of the thickest part of the wall was marked as the site of crack initiation. A second precaution was that the crack was also initiated on the "left hand end" of the pipe, when the lettering on the pipe surface was legible and not "upside down". These two precautions were taken to make the tests as reproducible as possible.

Results

Physical Ageing at Elevated Temperatures
Samples taken from the 110 mm pipes 6-009 (optimally gelled) and 6-023 (over-gelled) were oven aged in air during up to 200 days at 50 and 42.5 °C and up to 700 days at 35 °C. Next the aged samples were analysed using DSC.

DSC Measurements
An example of a DSC curve of a physically aged PVC sample is shown in Figure 1.
The dotted line is for the same PVC sample, which had become rejuvenated during the first heating. By subtracting the two thermograms the peak caused by ageing (in this example around 85 °C) can be studied separately. Another peak at around 43 °C also disappears after rejuvenation. It remains at an almost constant temperature during all further oven ageing. It may be that this peak is caused by prolonged low-temperature ageing in the soil (below 20 °C) [3]. This is not further discussed.
The temperature of the peak (T_{max}) in the DSC difference curve and its height (H) were determined as a function of ageing time, for both pipes. The measured T_{max} values are plotted in Figure 2 and the H values in Figure 3. There is no statistically significant difference between the two PVC pipes. This illustrates that – at least in the region between optimum gelation and over-gelation - the degree of gelation does not influence the ageing phenomena in these pipe samples.
The data on the peak heights (Figure 3) shows scatter below 200 days at 35 °C. At this ageing temperature the DSC peaks have a relatively low intensity and their height cannot be measured very accurately. However, at longer ageing times the peaks become more pronounced and the scatter is reduced.
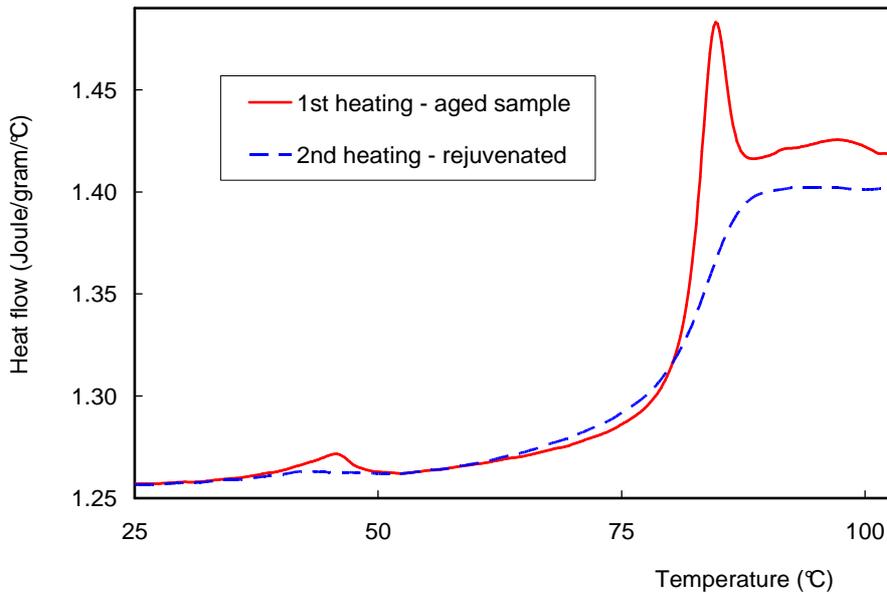
Figure 1. DSC curves of - further aged - excavated PVC pipe (solid curve) and the second heating curve of the same sample (dashed curve).
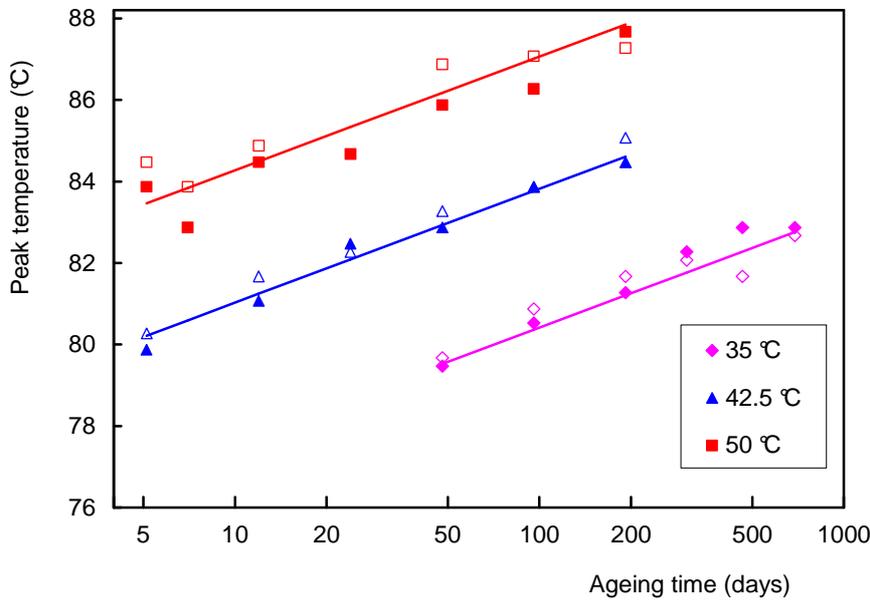

Figure 2. DSC peak temperature (T_{max}) of excavated PVC pipe 6-009 (open symbols) and 6-023 (closed symbols) as a function of ageing time and temperature. Solid curves: fitted model based on all three ageing temperatures.
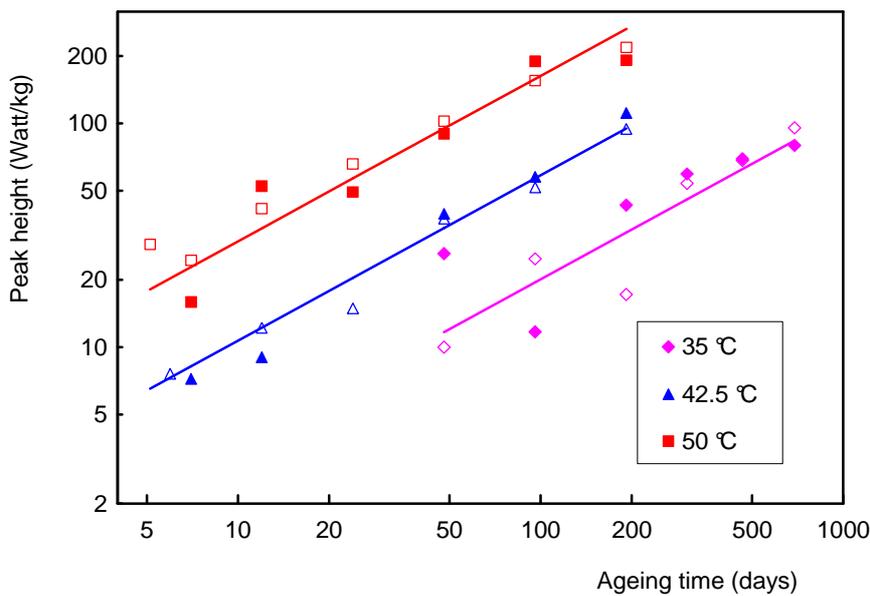

Figure 3. Height of the ageing peak in the DSC curve of PVC 6-009 (open symbols) and PVC 6-023 (closed symbols) as a function of ageing time and temperature. Solid curves: fitted model based on all three ageing temperatures.

Modelling

With a multi-variate statistics software programme [11] a model was derived using all of the data shown in Figure 2 and Figure 3. The result for T_{max} is given in equation (1):

$$T_{max} = A + B / T_a + C \log(t) \qquad (1)$$

A second equation (2) was derived using the same software for the height H of the DSC ageing peak:

$$\text{Log}(H) = D + E / T_a + F \log(t) \qquad (2)$$

T_a is the ageing temperature in Kelvin and t the ageing time in days. Please note that all logarithms are to the base of 10.
The values of the constants A until F in these equations are given in Table 1.

Table 1. Values of the constants in equations 1 and 2
calculated using multi-variate statistics.

Equation 1	Value	Equation 2	Value
A	218.039	D	19.437
B	-44.128	E	-6.044
C	2.791	F	0.740
R (corr. coeff.)	0.968	R (corr. coeff.)	0.930

The model lines for T_{max} as calculated with equation (1) were added to Figure 2 and those for H as calculated with equation (2) were added to Figure 3. The values of the coefficients A until F differ only marginally from those calculated earlier with fewer data points at 35 °C [3].

Water absorption of PVC pipes

It was noted that excavated PVC pipes may have absorbed some water. The maximum water content of these pipes was investigated further, to be able to assess its possible influence on the properties.
A sorption-desorption experiment as described under "Materials and methods" was performed. The foil's infrared spectrum was measured at different water contents, which water content was calculated from the weight change.

Figure 4 shows the infrared spectra at different water contents. In two regions band intensities decrease simultaneously as a result of a decreasing water content. These are the broad O-H stretch band centred in the vicinity of 3420 cm^{-1} and the H-O-H bending band to the left of 1600 cm^{-1}. The broadness of these peaks indicates hydrogen bonded water in the PVC. By subtracting the spectrum of the dried PVC sample from that of the same sample in water-saturated condition more details can be discerned, as is shown in Figure 5. Sharp peaks or shoulders at 3673, 3588 and 1607 cm^{-1} are noted. These frequencies are the same as reported by Kusanagi et al [12] and are also typical for water in PVC, because these authors found that water band frequencies are closely linked to the polymer matrix in which the water is absorbed. However, broad water bands centred at 3418 and 1644 cm^{-1} are also present.
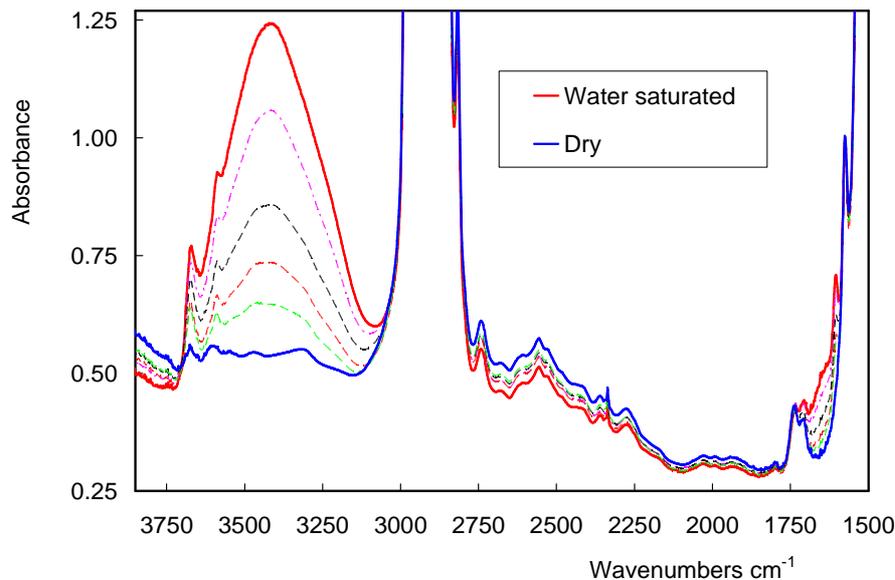
Figure 4. FTIR spectra of a thin PVC sample with (from top to bottom) decreasing water content.
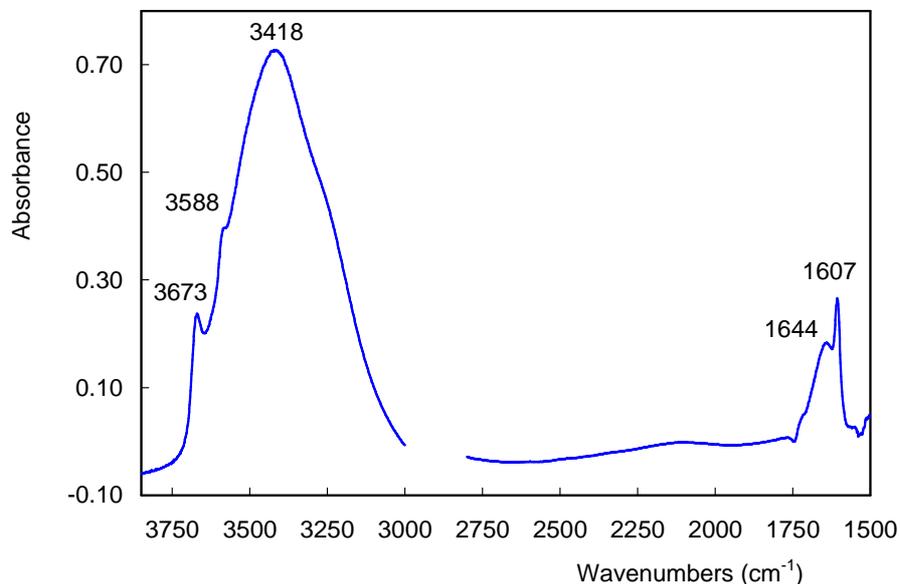

Figure 5. FTIR spectrum of a water-saturated PVC foil minus the spectrum of the same foil in dried condition. The region between 3000 and 2800 cm^{-1} was left out because of the poorly compensated huge PVC peaks in Figure 4.

This means that in the water-saturated PVC pipe sample two types of water are present. The first type is a relatively low content of water molecules that have appreciable interactions with the PVC matrix [12]. The second type consists of relatively large clusters (on a molecular scale) of water which is - to a large extent - isolated from the PVC matrix, showing the normal peak broadening due to hydrogen bonding to other water molecules and absorbing at 3418 and 1644 cm^{-1}. These values are relatively close to those of Kusanagi et al, who found bands at 3430 cm^{-1} and 1650 cm^{-1} for liquid water. The band they noted at 3210 cm^{-1} is also present in Figure 5, but only as a poorly resolved shoulder.

Maximum Water Uptake of PVC Pipes
Table 2 shows the maximum water content after submersion in water, with respect to previously dried, as-received samples of uPVC pipes from different production years. The as-received pipes contain 0.04 - 0.11 % water, which is lost by drying with silica gel. It must however be realised that it is unknown how much water may have been lost during storage before water content measurement was carried out. The data on the water content of the as-received pipes is therefore only indicative.

Table 2. Excavated PVC gas pipe samples from different production years after complete drying in silica gel followed by submersion in water at 21 °C until saturation.

Production year	Number of samples	Average weight change at 0% RH	Stand. dev.	Maximum water uptake (%) in water	Stand. dev.
1957	3	-0.08	0.02	0.57	0.02
1962	5	-0.07	0.02	0.54	0.04
2000	1	-0.04	-	0.10	-

The older pipes from 1957/1962 can absorb more than five times as much water (up to saturation) compared to the relatively modern unused pipe from 2000.

Carbon Dioxide in PVC Pipes
An unknown sharp peak at 2335 cm^{-1} was noted several times in the FTIR spectrum of excavated PVC gas pipes and also in some water pipes. It is always accompanied by a second peak of lower intensity at 2323 cm^{-1}. This is illustrated in Figure 6. The intensity of this doublet is variable between different pipe samples and can also be zero (sample 5-020).

One sample from the series shown in Figure 6 was investigated further (5-026). After cutting a new sample, spectra were repeatedly taken of the same foil, but after varying time periods in a dry nitrogen atmosphere. The resulting spectra are shown in Figure 7. In two hours about three quarters of the intensity of the mentioned doublet is lost. This suggests a dissolved gas or vapour which gradually evaporates.

To investigate whether the noted doublet is due to carbon dioxide gas which is dissolved in the PVC, a foil sample was exposed to nitrogen containing 30% carbon dioxide. After different exposure times the foil was taken out of this atmosphere, measured with FTIR spectroscopy in an atmosphere containing only nitrogen and then placed back in the atmosphere containing 30 % CO_2 gas. The results are shown in Figure 8. The same doublet that is lost on desorption (Figure 7) is appearing due to carbon dioxide absorption (Figure 8).

The spectrum of carbon dioxide which is dissolved in PVC must be distinguished from that of free carbon dioxide gas in the air surrounding the sample. At 2361 and 2340 cm^{-1} carbon dioxide gas shows a well-known double absorption band, often found in infrared spectra as an unwanted disturbance. All spectra in this publication have been carefully corrected for any gas phase CO_2 bands.
Therefore, it is now proven that the sharp peaks at 2335 and 2323 cm^{-1} found in many excavated PVC pipes are due to carbon dioxide to varying degrees.

It was noted that whilst the PVC foil in Figure 8 shows large differences in the peak intensity at 2335 cm^{-1} due to dissolved carbon dioxide, it only shows minute weight changes. Therefore, weight change measurements were performed on 12 test bars machined from the unused pipe from 2000 in Table 2 (6-030), each bar having a thickness equal to the original pipe wall thickness (3 mm). The length of the test bars was 80 mm and the width was 10 mm, according to ISO 8256. The weight of all 12 test bars together was recorded during about 600 days exposure to 100 % carbon dioxide gas with 100 % RH (relative water vapour content). The result is shown in Figure 9.
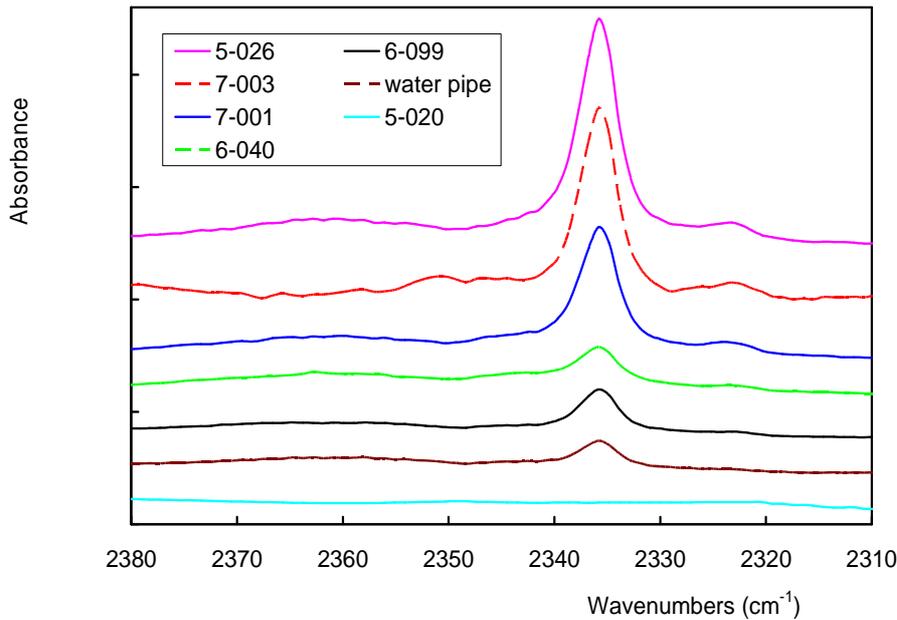
Figure 6. Small part of the FTIR spectrum of 6 excavated PVC gas pipes and one water pipe containing a sharp band at 2335 cm^{-1} and a smaller one at 2323 cm^{-1} with varying intensity. The spectra have been shifted in vertical direction for clarity. One tic mark on the vertical scale is 0.05 Absorbance units.
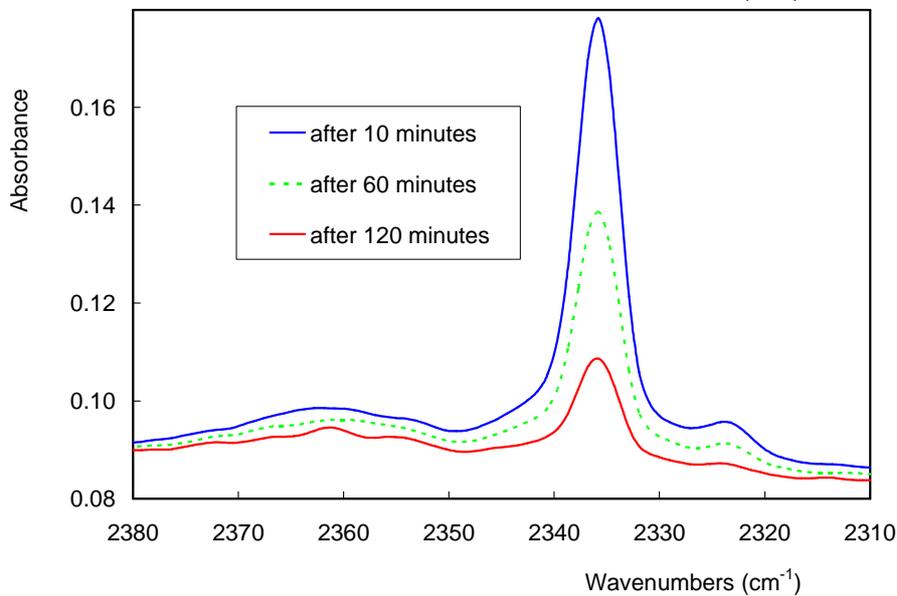

Figure 7. Small part of the FTIR spectrum of a foil sample cut from a PVC pipe. The spectra were taken 10 minutes (top), 60 and 120 minutes (bottom) after cutting. A continuous decrease in intensity of the doublet at 2335 and 2323 cm^{-1} illustrates a desorption process.
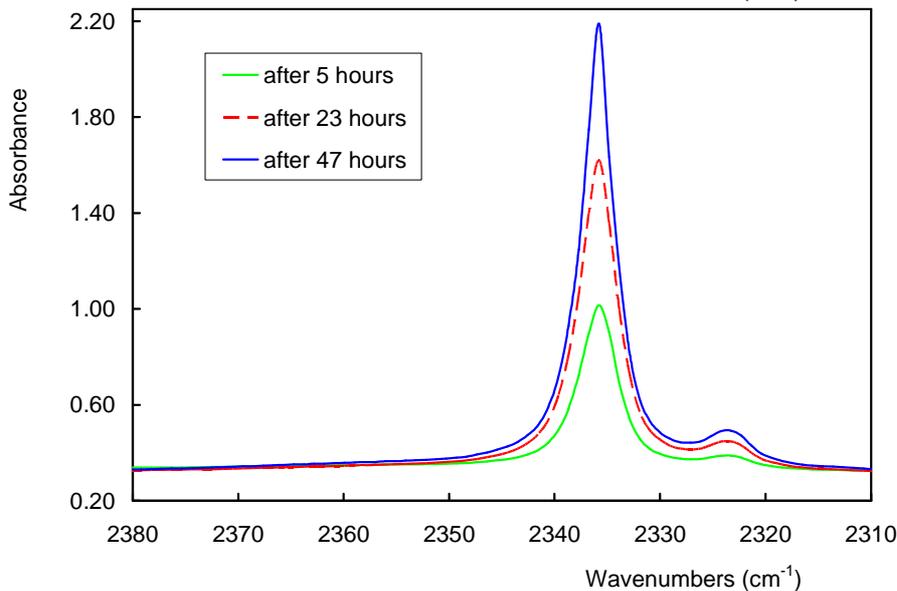

Figure 8. FTIR spectra of a PVC foil after varying times in 30 % carbon dioxide in nitrogen showing an increased intensity of the doublet at 2335 and 2323 cm^{-1} with increasing exposure time.
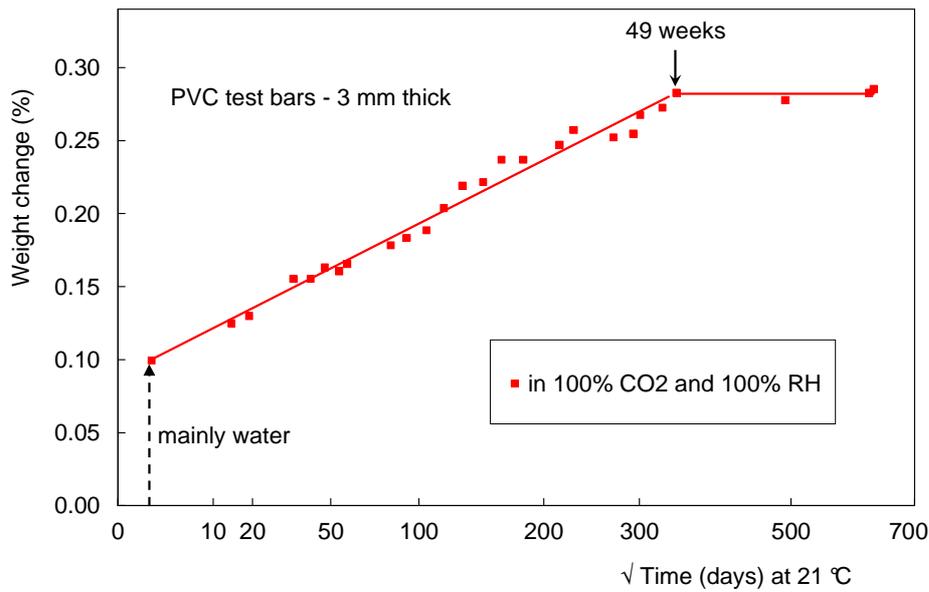
8

Figure 9. Carbon dioxide and water absorption of PVC pipe 6-030 (wall thickness 3 mm) at 21 °C. The time axis is the square root of the time in days. Only after about 49 weeks saturation is reached.

Part of the initial weight increase is due to water absorption. From Table 2 it is known that for this pipe the maximum water absorption is 0.10 %. The weight increase above 0.10 % must therefore be due to carbon dioxide absorption. Only after about 49 weeks the carbon dioxide gas absorption of PVC is completed. The absorption process at a wall thickness of 3 mm is rather slow and this is also likely the case for desorption.
In future, the influence of water and carbon dioxide absorption on the impact properties of excavated uPVC pipes will be assessed.

Wall Thickness Variations
The wall thickness was measured at 12 locations around the circumference of the pipes. Figure 10 shows an example. A sinus was fitted through the data points.
Wall thickness variations in other pipe samples were determined as well. Table 3 gives an overview.
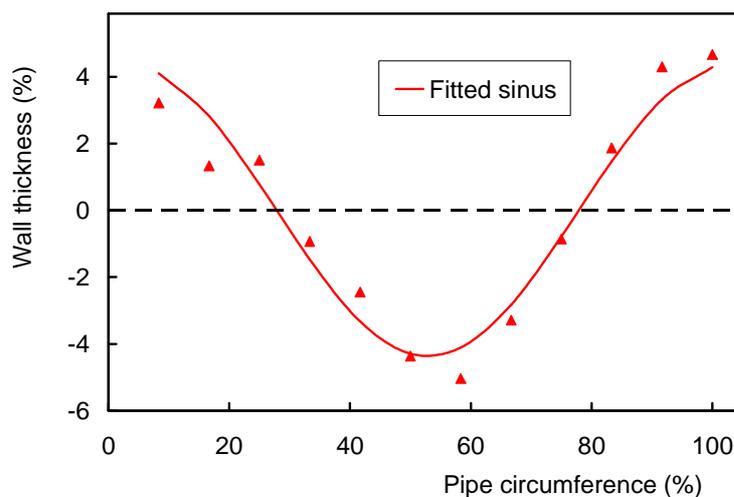

Figure 10. Wall thickness variations (in %) over the circumference of a 315 mm PVC water pipe, measured at 12 locations.

Table 3. Maximum wall thickness variation in PVC gas and water pipes.

Gas pipes	Diameter (mm)	Max. thickness variation (%)	Water pipes	Diameter (mm)	Max. thickness variation (%)
5-024	110	4.1 and 4.2	6-001	315	4.0
7-004	110	0.9 and 1.3	6-012	110	0.5
8-002	110	4.3 and 4.6	8-123	200	1.1
9-047	63	2.4	8-003	250	1.2
9-156	200	0.6	8-122	315	2.4
10-160	110	3.2	10-053	315	1.4
			10-052	315	7.1

S4 Tests

Figure 11 shows several failed water pipes after occurrences of Rapid Crack Propagation in practice.

Figure 11. Several uPVC water pipes after RCP in practice. Crack length up to 10 meters.
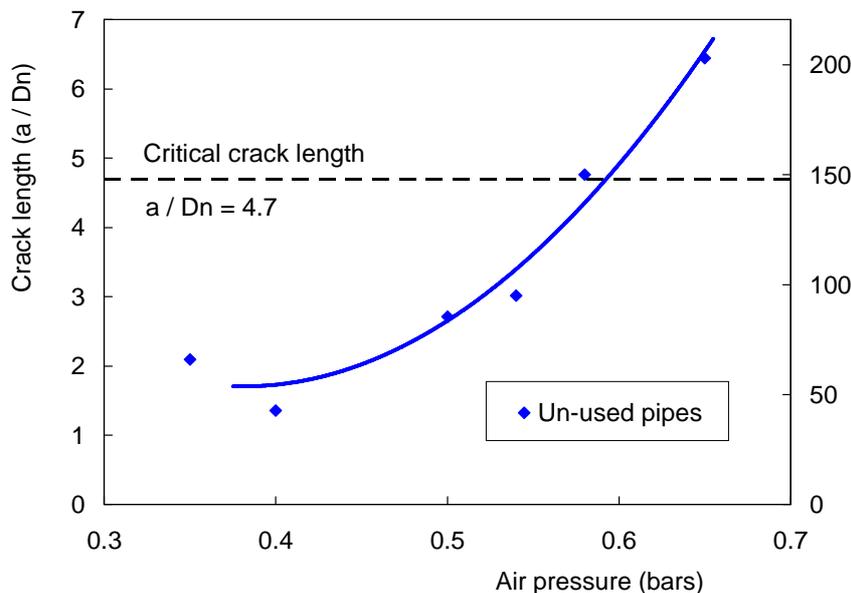

Figure 12. Crack length in the S4 test (left: relative to the pipe diameter and right: in cm) measured on unused 315mm uPVC pipes produced in 2010. In all cases the cracks were initiated at the location in the pipe circumference with the thickest wall.

These incidents in buried pipes triggered an investigation into RCP in uPVC water pipes. The method used was the S4 test, as it is a standardised test method, according to ISO 13477. Unused 315 mm uPVC water pipes produced in 2010 were tested. At this diameter, the pipe length should be 2.46 m. The tests were performed at 0°C and at several air pressures.

The crack length in the pipe as a function of the air pressure inside the pipe is given in Figure 12. According to ISO 13477 the transition between crack arrest and rapid crack propagation occurs at a relative crack length of 4.7 (with respect to the nominal pipe diameter) and an absolute crack length of 148 cm (for 315 mm pipe). At this diameter the Critical Pressure in the S4 test is around 0.58 bars.

In the transition region between crack arrest and crack propagation (between 0.5 and 0.65 bars) the scatter in the data points is relatively low (about 0.05 bar), in comparison with measurements - also performed in the author's laboratory - on another pipe for which the initiation site had been chosen randomly (about 0.25 bar [13]).

Discussion

Activation Energy of the Ageing Process
To check the results on physical ageing the apparent activation energy was calculated from constant E in equation (2) (see Table 1). A value of 116 kJoule/mole was found for the two uPVC gas pipe materials together. This value is very close to the value of 115 kJoule/mole, the activation energy for ageing of uPVC pipes which was assessed by Visser et al [4] using tensile tests on aged samples.

Water Absorption
There are similarities as well as discrepancies regarding the FTIR spectra of water in PVC pipes with respect to the results of Kusanagi et al [12]. The sharp peaks of water with much interaction with PVC at 3673, 3588 and 1607 cm^{-1} are present in Figure 5 at the same frequencies as noted by Kusanagi et al.

However, in their paper the broad hydrogen bonded water bands in Figure 4 and Figure 5 are absent. It is likely that this is due to the different manner of introducing water in the PVC samples. Kusagani et al have used air with a relative humidity of only 65%, whilst the results in Figure 4 and Figure 5 have been obtained by submersion in liquid water. The latter procedure likely introduces more water into the PVC matrix, which is also partly isolated from the polymer matrix and more associated with itself in clusters.

Nowack et al [14] describe investigations on very old PVC pipes which had been installed before World War II and were tested after excavation. They report maximum water absorption values for pipes which had been used between 1937 and 1961 and found values of 3.4 and 3.5 %, which seem to be rather high. They also investigated a more modern pipe which had been used between 1959 and 1984 and report a value of 0.18 % for this pipe, which corresponds somewhat better with the results in Table 2.

It is known that the resins in the very old PVC pipes from 1937 that were investigated by Nowack et al were made with an emulsion polymerisation process, whilst the more modern PVC pipes, produced after about 1960/1965, were made from resins produced using a suspension polymerisation process [15]. It may be speculated that emulsifier residues in E-PVC pipes are responsible for the higher maximum water uptake of the old PVC pipes in

comparison to the more modern pipes made from S-PVC resins, which contain no or less of such residues.

In future it will be assessed whether the noted differences in water content influence the mechanical properties of excavated PVC pipes.

Carbon Dioxide Absorption by PVC Pipes

From Figure 6 until Figure 9 it can be concluded that PVC can absorb carbon dioxide gas, even at atmospheric pressure and that this effect can be illustrated by FTIR spectroscopy and weight increase. Conversely, desorption can be measured in the same way.

Chiou at al [9] mention that carbon dioxide is considerably more soluble in glassy polymers including PVC than helium, nitrogen, argon and methane. Berens and Hodge [2] also report that PVC absorbs carbon dioxide. They estimate that at atmospheric pressure the maximum content is about 0.2 weight percent at 40 °C. The value of 0.19 % at 21 °C derived from Figure 9 agrees relatively well.

Absorbed carbon dioxide also depresses the glass transition temperature of PVC which proves that it functions as a plasticizer for PVC [9, 10]. Based on this it may be expected that the content of dissolved carbon dioxide also influences the impact resistance of PVC pipes. The magnitude of such an effect in PVC will be investigated in future.

It is also possible that the rate of physical ageing of PVC is increased by CO_2 absorption.

Possible Sources of Scatter during Measurements

Hermkens et al [7] have published impact resistance data of excavated PVC gas pipes. The average impact energy they found was 126 kJoule/m^2 and the standard deviation was 26 kJoule/m^2. The reason for this relatively high standard deviation is not yet understood. However, it has now become clear that PVC pipes may contain variable water and carbon dioxide contents. Water will have been absorbed from groundwater and rain. It may be speculated that carbon dioxide originates from biological processes in the soil surrounding the pipes. The content of water and carbon dioxide also depends on evaporation during storage on site and in the lab.

It is now conceivable that the impact energy values mentioned above are influenced by varying water and carbon dioxide contents of the tested PVC samples. Another factor may be the resin type which was used for making the pipes (E-PVC and S-PVC with their K-values of 73-75 and 67 respectively [15]).

Further work will be performed to assess the influence of the above variations.

RCP Tests

It is well known that pipe diameter and wall thickness have a large influence on the Critical Pressure in the S4 test. The Critical Pressure decreases with increasing diameter and wall thickness, which makes larger diameter pipes more vulnerable to RCP.

Thickness variations over the pipe circumference are normal (Figure 10 and Table 3). Excluding a possible source of scatter in the data, by always initiating fracture at the location of the thickest part of the wall, has a favourable effect. It now appears that choosing this location is important for S4 tests, because the scatter is only ± 0.05 bars whilst previously, when no attention was paid to wall thickness variations, the scatter was ± 0.25 bar [13].

It is very important to realise that the Critical Pressure in RCP testing is dependent upon pipe length and the rate of decompression of the medium inside the pipe (air or water). This means that the Critical Pressure in the S4 Test - Pc (S4) - must be multiplied by a large factor to arrive at the Critical Pressure in the Full Scale Test - Pc (FS) - for instance for pipe lengths of

10 meters in between mechanical joints. For PVC pipes this factor is unknown, but for PE pipes the formula is given in EN 1555-2:

$$Pc\ (FS) = 3.6 * Pc\ (S4) + 2.6\ (bars) \qquad (3)$$

Conclusions

1. A quantitative DSC model was set up based on ageing experiments on two types of excavated PVC pipe. With the model the influence of ageing temperature and ageing time on the height and location of the endothermic DSC ageing peak can be described. Both the optimally gelled and the over-gelled PVC pipes can be described by the same parameters using this model.
2. Old PVC gas pipes, installed in 1957 and 1962, show a water uptake at saturation of 0.5 to 0.6 %, whilst a modern pipe from 2000 shows a maximum water uptake of only 0.1 %. It will be investigated how large the plasticizing effect of water on the impact properties of PVC pipes is.
3. Excavated PVC pipes may also contain dissolved carbon dioxide gas. This leads to a plasticizing effect in PVC as well. The uptake is rather slow. Any influence of the carbon dioxide content on the impact properties of PVC pipe will be determined in future.
4. The Critical Pressure in the S4 Test of unused 315mm SDR41 uPVC water pipes is 0.58 bars. However, this value is only valid for a limited pipe segment length of 2.46 meters, at 0 °C and with the pipe filled with air. Conversion to longer pipe lengths will increase the Critical Pressure quite remarkably. Water instead of air as internal medium will also be influential.
5. For S4 Tests in PVC pipes it is recommended to first assess the location in the pipe's circumference where the wall is the thickest and then initiate fracture only there. It appears this precaution leads to far less scatter in the data.

Acknowledgements

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