RESIDUAL QUALITY OF OLD UPVC GAS AND WATER PIPES

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The condition of 35-50 years old uPVC main (110 mm, SDR21) and service pipes (32 mm, SDR13.6) for gas and water distribution was assessed. From 27 excavations about 400 segments of 1.2 meters' length were tested. The K-value, the degree of gelation and the relative calcium carbonate concentration were measured. Residual pipe stresses in hoop direction (Janson method) still are relatively high (3.9 – 6.6 MPa) and these have a small negative influence on the impact resistance and the resistance to internal water pressure. Still, all pipes meet the requirements of Hydrostatic Pressure tests at 20 and 60 °C. Tensile Impact tests show good results. The old pipes can also be solvent-cemented again.

The Critical Pressures (Pc) at 3 °C in Rapid Crack Propagation (RCP) testing of water-filled uPVC pipes (hydrostatic S4 test per ISO 13477) is remarkably high (Pc = 5.75 – 8.25 bars). By comparing with results of various other hydrostatic S4 tests it was clearly found that Pc increases when the relative wall thickness increases (decreasing SDR). This explains why in the present investigation the Pc values of the old thick-walled SDR21 pipes are favourably high. No influence of the diameter (110 – 315 mm) on Pc was noted. Other authors confirmed similar high Pc values (7 bars) in the hydrostatic S4 tests on new SDR18 water-filled uPVC pipes.

The operation pressure has no influence on pipe quality. No influence of ageing was found. Key parameter is the initial extrusion quality, which mainly influences the brittle-ductile transition in the Tensile Impact test.

The investigated uPVC pipelines can still be used during several decades to come.

INTRODUCTION

The use of uPVC pipelines in German gas and water distribution grids mainly started in the 1950s. Some pipeline systems have therefore already passed the end of their projected service life of 50 years, but statistics maintained by the utilities do not point to any ageing-related failures. Thus, network operators are faced with the question of how to determine the reliability of these pipelines and how to deal with these grids in the future. The incident rate for uPVC water pipes in Germany is very low, at only 0.025 per km per year [1]. Also for uPVC gas pipelines the incident rate is low, at less than 0.05 per km per year and falling to about 0.03 in recent years [2].
The goal of the present investigation is to assess the residual quality of the old gas and water uPVC pipelines, including joint quality. The approach is to apply material and functional tests to assess the residual quality and to determine which tests provide adequate information.

MATERIALS, EXPERIMENTAL AND STATISTICAL METHODS

Pipe materials

Nine excavations of 32 mm SDR13.6 uPVC gas pipes used for service connections at 0.8 – 1 bar, nine excavations of 110 mm SDR21 uPVC gas mains (0.09 – 1 bar) and nine excavations of 110 mm SDR21 uPVC water mains (3.5 – 10 bar) were investigated. These pipes were excavated from the grids owned by the distribution companies mentioned in the Acknowledgements. Each of these 27 sets contained between 10 and 30 meters of pipe. In total about 500 meters of pipe and about 70 solvent-cemented joints were excavated.

Materials characterisation methods

The K-value of five uPVC samples was determined per ISO 1628-2. DSC was used at 20 °C/minute to assess the extrusion temperature [3] of the pipes.
The Dichloromethane Temperature (DCMT) test per EN 580 was used to assess the degree of gelation. This test was modified by using a combination of either 10 and 5 °C or 10 and 15 °C as testing temperatures. This allows assessing 4 levels of gelation (Table 1) instead of "pass/fail".

Table 1. Gelation class, determined using the modified DCMT [4]

Gelation class	Attack at:
1: very poor	5 °C
2: under-gelled	10 °C
3: relatively high	15 °C
4: very high	No attack at 15 °C

FTIR transmission spectroscopy was performed on thin slices cut from the pipes.

Mechanical testing

The Janson method [5] was used to assess residual stresses in tangential direction. Residual deformations in the axial direction were determined on a segment after 1 hour at 150 °C [6]. Further ageing was applied by placing samples in an oven for 1 or 2 weeks at 50 or 60 °C [7,8].
Hydrostatic Pressure (HP) tests per ISO 1167 were applied at 20 °C (hoop stress: 42 MPa) and at 60 °C (hoop stress: 10 MPa) and compared to the requirements in DIN 8061.
Two types of impact tests were applied:

1. Rapid Crack Propagation (RCP) tests using the hydrostatic S4 test [9] on the 110 mm water pipes, which were filled with water/propylene glycol as in previous investigations [10,11], at 3 °C. Baffles were not used, as they are superfluous for water-filled uPVC pipes [11,12]. The

result is the Critical Pressure Pc, the internal water pressure at which the crack length exceeds the critical length of 4.7 times the diameter. The crack speeds are very high, up to 500-600 m/s [24]. Of each of the nine excavation sites of the 110 mm water pipes, typically eight segments were tested with the S4 test, to determine Pc. In total 80 segments were tested, because for one excavation site the influence of ageing was tested as well.

2. Tensile Impact Tests [13,14] on non-notched test bars cut from the gas pipes only (32 and 110 mm). The result is the temperature T_{bd} at which the brittle-ductile transition occurs when measuring from –30 to +50 °C. A lower T_{bd} means a higher impact resistance.

Twenty-two solvent-cemented joints were tested for shear strength and a homogeneous solvent-cement distribution. The results were good and have been published previously [4,15,16].

Correlations between various variables were sought, because this improves understanding and the evaluation of the results. Often Univariate Statistics was applied, using a formula such as:

$$y = a + b * x \qquad (1)$$

From equation (1) a correlation coefficient R is calculated, which should preferably be close to 1. No correlation means R = 0. When R is low, there may either be no correlation or, and this is very important to realise, other variables may play a part as well, simultaneously. Multi-Variate Statistics (MVS) must then be used [17,18]:

$$y = a0 + a1 * x1 + a2 * x2 + a3 * x3 \; (+ \ldots\ldots) \qquad (2)$$

In equation (2), *y* depends on 3 independent variables. Again, R is important, but also the Probability P. Each variable *x1* through *x3* has its own P. P is the probability that there is no correlation at all [18]. It is required that $P < 0.05$, which means 5% chance that there is no correlation, which is the same as 95% chance that there is a correlation indeed.

Table 2. Measured pipe properties and those required for new pipes. See also [15,16].

Property	Requirement	Found
Diameter, wall thickness, ovality	Fulfil DIN 8061	Few exceptions due to service
LRT (length change after 1h at 150 °C)	< 5% **	0.6 – 8.9 %
Janson-stress (110 mm)	-	3.9 – 6.6 MPa
Janson-stress (32 mm)	-	5.6 – 9.4 MPa
Degree of gelation (dichloromethane)	No attack (15 °C)	Some pipes are poorly gelled
DSC (extrusion temperature)	-	Rather variable: 167-209 °C
K-value	> 65	68.9 (0.2), n = 5
Tensile Impact Test	-	T_{bd} = -7.5 until 25 °C
HP test at 20 °C (42 MPa)	> 1 hour	3 - 143 hours
HP test at 60 °C (10 MPa)	> 1000 hours	> 1150 h.
RCP (S4) test - 110 mm water pipes	-	Pc = 5.75 – 8.25 bars

RESULTS

Table 2 summarises the results. The pipes still meet the most important requirements in the modern standards and this is a very positive result. More details are presented below.

Characterisation of the materials

The K-value of five selected samples was the same: K = 68.9 (st. dev. = 0.2), although slightly higher than in other cases in which K = 66 is used for pipes.

Chalk (calcium carbonate) particles were found in some pipes, as indicated by the peak at 875 cm^{-1} in the FTIR spectrum. In the present population, chalk was noted for the first time in pipes installed in 1972, in about half of the pipes. Nowadays, adding chalk is state of the art.

Large variations in the degree of gelation exist. Figure 1 shows a trend (R=0.78) linking the extrusion temperature and the DCMT, but there is also scatter.

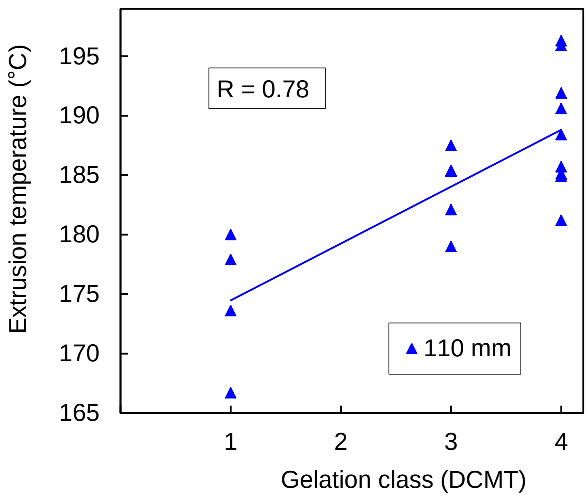

Figure 1. The extrusion temperature (DSC) versus the gelation class (Table 1) in the DCMT (110 mm gas and water pipes).

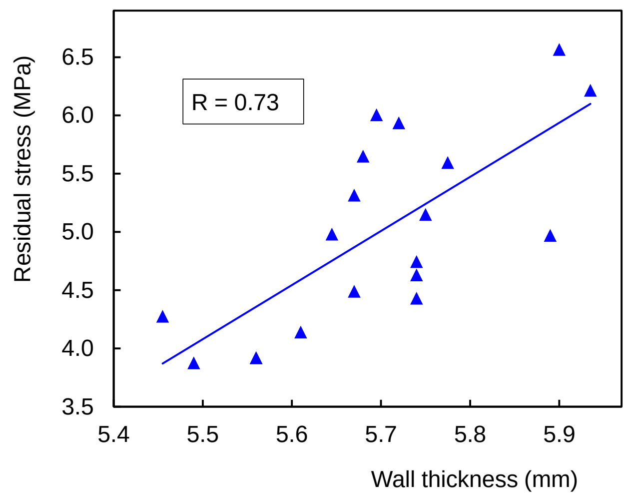

Figure 2. The Residual Tangential Stress (Janson stress) versus the wall thickness of 110 mm gas and water pipes.

Residual stresses

The wall thickness of the 110 mm pipes varies slightly (*Figure 2*) but meets the requirements. The Janson stress increases with increasing wall thickness, as predicted by Janson [5], even in this narrow range. Some pipes show frozen-in strain in axial direction [6], but the mechanical properties were not influenced.

Impact tests

The Pc values in the S4 test at 3 °C conducted on water-filled excavated 110 mm SDR21 water pipes are high, at between 5.75 and 8.25 bar. This is a good result (see Discussion).

Table 3 shows that further ageing for 1 week at 60 °C [7,8] of 8 pipe segments for the S4 test has no influence on Pc.

Table 3. Critical pressure Pc before and after oven-ageing of uPVC water pipe segments

	As received	After oven-ageing for 1 week at 60 °C
Pc (bar)	6.0	6.15

Figure 3 shows a typical result of the Tensile Impact test. Testing at progressively higher temperatures changes the fracture behaviour from brittle to ductile, at the brittle-ductile transition temperature T_{bd}. The mechanical energy needed for failure increases from about 300 to about 750 kJoule/m^2. This step in impact energy is similar for all excavated pipes. Only T_{bd} is variable.

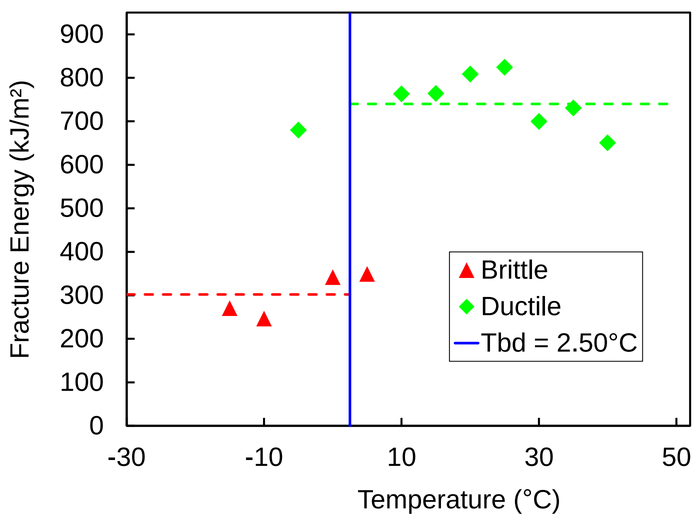

Figure 3. The fracture energy in the tensile impact test as a function of temperature. Each test bar was tested at another temperature. The scatter in T_{bd} is typically ± 5 °C.

DISCUSSION

Characterisation tests

The high K-value (69) of the pipes means that some properties will be better than for pipes made from K67-uPVC. This was not investigated further in the present study.
Some pipes are poorly gelled. Despite this, no influence of the degree of gelation on the properties was noted. This is not understood.

Residual Stresses

Janson [5] published about residual stresses in the tangential direction (consisting of a tensile stress near the internal surface and a compressive stress near the external surface), also denoted cooling stresses. They are still present in the tested pipes, even 30 to 55 years after installation. Considerable cooling stresses (between 3 and 6 MPa) have also been noted in excavated (first

generation) PE50 pipes [19]. Janson writes [5] that the cooling stresses increase with - amongst other factors - a thicker pipe wall. This is indeed reflected in Figure 2.
The cooling stresses tend to have a negative influence on the brittle-ductile transition T_{bd} of 110 mm gas pipes (*Figure 4*). The scatter is high because only 9 pipes were tested.
On the other hand, it was assessed that the stresses in the axial direction have no influence on T_{bd} (R=0.09). This means that these two types of stresses have a different influence. This is consistent with findings by Janson, who remarks [5]: “The standard heat reversion tests (=Longitudinal Reversion Tests [6]) do not reveal stresses of the type described here” (in tangential direction).

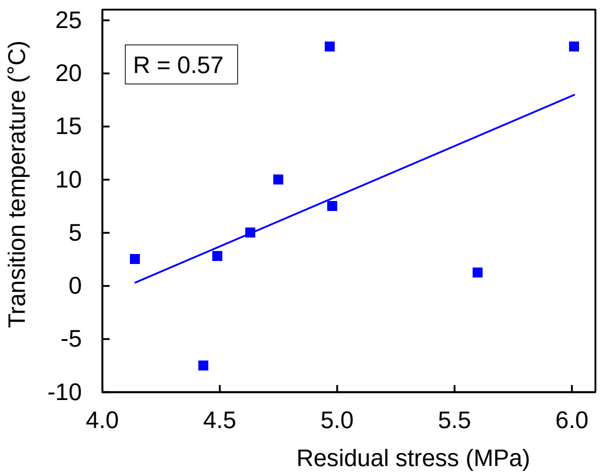

Figure 4. The brittle-ductile transition temperature T_{bd} of 110 mm gas pipes tends to increase slightly with increasing Janson stress.

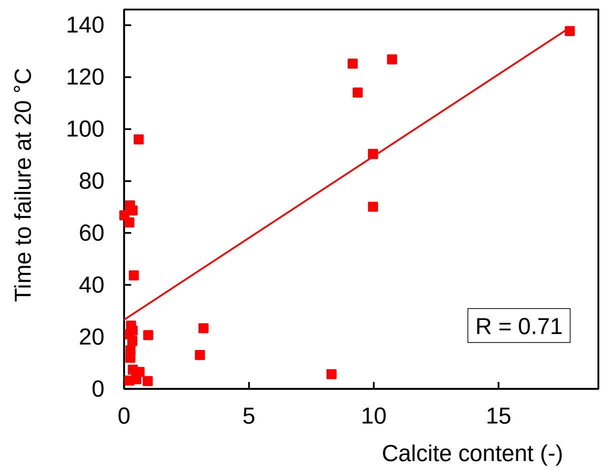

Figure 5. A higher content of chalk particles tends to increase t_{fail}, the time to failure in the short-term HP test at 20 °C in al 27 data sets.

Test methods for the long-term behaviour

All 32 mm and 110 mm pipe segments meet the requirements of the HP tests at 20 and 60 °C for new uPVC pipes. The resistance against internal pressure is therefore still excellent. This is a very important finding of the study and it confirms earlier results obtained by *Alferink et al* [20].

Multivariate statistics

Figure 5 shows that the time to failure in the HP test at 20 °C (t_{fail}) tends to increase with a higher chalk content. The first row in Table 4 gives the uni-variate equation. This correlation is expected. Chalk particles are harder than uPVC and increase – as any hard filler - the stiffness of the polymer material. Certain chalk types also increase the impact resistance [21,22].

The equation in the second row in Table 4, describing the influence of the wall thickness *e* on t_{fail}, shows a lower correlation coefficient and hence a larger standard error of prediction. There is common belief that a thicker wall has a positive effect in the HP test, despite the usual correction for the wall thickness (constant hoop stress).

Table 4. Illustration how t_{fail} at 20 °C in the Internal Water Pressure Test can be correlated with either the content of chalk filler ([Ca]) or wall thickness (e). Correlating both variables provides the highest R. For all variables, P is favourably low and meets the requirement P < 0.05.

Correlation equation	R	P	Standard error of prediction (h)
t_{fail} = 26.630 + 6.283 * [Ca]	0.707	<0.001	31.5
t_{fail} = -32.508 + 17.362 * e	0.591	<0.001	35.9
t_{fail} = -15.699 + 4.928 * [Ca] + 10.071 * e	0.770	0.001 & 0.024	28.9

A positive influence of an increased wall thickness was also found in Point Load tests on PE50 pipes [23]. The latter may be attributed to the notion that in a thicker pipe wall a slowly growing crack needs to travel a longer time through the pipe wall before failure eventually occurs.

The influence of both variables is combined in the bottom row of Table 4. The correlation coefficient is not between those for each variable alone, but rises to 0.770. The standard error becomes smaller than in the two previous cases as well. This means that part of the scatter in *Figure 5* is no scatter at all, but is due to small wall thickness variations. This illustrates the advantage of taking a wider perspective by applying Multi-Variate Statistics.

It was found that adding even more variables to the correlation equation at the bottom row of Table 4 causes too large values of P (P>>0.05). Variables such as the operating pressure, the number of years in operation, the degree of gelation and the extrusion temperature were therefore excluded from further statistical analysis, because they have no systematic influence. Checks were made to determine if the product of the operating years and the maximum operating pressure (as a new variable describing the intensity of prolonged loading) has an effect, but, again, P >> 0.05.

<u>*RCP tests*</u>

Previously, 315 mm water-filled uPVC pipes were also tested using the S4 test at 3 °C [11]. Based on these tests it was assessed that as the SDR went from 41 to 34 and then to 26 (increasing wall thickness) the value of Pc increases, from 1.95 bar to 4.4 bar (*Figure 6*).

Adding the Pc of the nine 110 mm SDR21 water pipes from the present project to *Figure 6* illustrates that Pc increases further with decreasing SDR, despite differences in diameter.
Choi and Marti measured the blue point [24] on 175 mm SDR18 pipes, which compares favourably. Their result provides independent confirmation of the red circles in *Figure 6*.

Leevers *et al* [26] used the Irwin-Corten equation to calculate Pc values for uPVC pipes. Although the values calculated in this manner deviate somewhat [4], an increasing Pc with decreasing SDR is also found. A similar increase of Pc with decreasing SDR was also the result of theoretical calculations by Breen [11]. Consequently, in all known cases of hydrostatic S4 tests on uPVC pipes, a lower SDR (larger relative wall thickness) consistently leads to a higher resistance to RCP. The ongoing "RCP debate" on water-filled uPVC pipes can now be settled. Those companies that apply thin-walled uPVC water pipes may encounter more RCP cases in practice than those that only use thick-walled uPVC pipes.

It is not surprising that there seems to be no significant difference between results with and without baffles. The present authors have left the baffles out, on purpose, as suggested by Leevers [12]. Because of the high crack propagation speed in water-filled uPVC pipe, baffles to suppress decompression during the test are superfluous [11]. *Figure 6* proves that this choice – only for water-filled uPVC pipes – was correct. This is further supported by Choi and Marti [25], who report a calculated decompression speed of 484 m/s. This is lower than the crack speed they report in the RCP region above Pc (500 – 600 m/s) in their Figure 10. Choi and Marti report a reduction of the decompression speed by using baffles from 484 down to 200 m/s, but with their measured crack speed of 500 – 600 m/s this is not anymore necessary. Baffles are therefore indeed superfluous in this case.

Attention was also paid to correlations between Pc and the installation year, operation pressure or the chalk content, but none were found (R<0.14).

Comparison with practice is very important. According to ISO 13477 Pc(S4) values may be converted to Full Scale Pc(FS) values, but this formula was only derived for PE gas pipes. There is no evidence that this formula is also valid for water-filled uPVC pipes, although Choi and Marti [24] use it. Moreover, because a similar conversion formula also lacks for Polyamides such as PA11, PA12 and PA6.12 gas pipes, only Full Scale RCP tests on PA pipes are prescribed in ISO 16486.

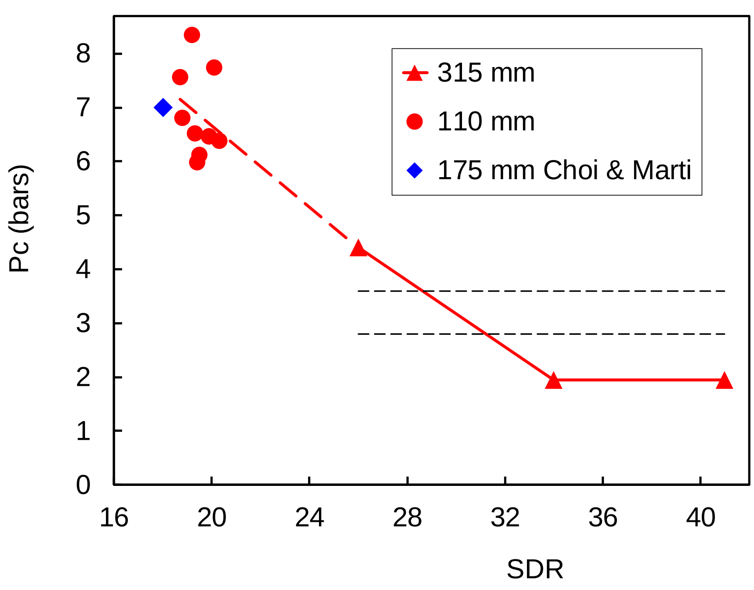

Figure 6. Influence of the SDR on the Critical Pressure of water-filled uPVC water pipes at 3 °C. Each data point is based on eight separate S4 tests. Red triangles: published previously [11,4]. Red circles: from the present investigation. All red points have been measured without baffles. The blue point is the Pc measured by Choi and Marti [24] on 175 mm SDR18 pipes with baffles. It fits well. Dotted lines: range of SDR values and operating pressures in cases of RCP in practice.

However, information about how S4 results of uPVC water pipes compare to practice is available. More than 70 practical cases of RCP failures in uPVC water pipes (SDR26-SDR41) have come to the attention of the first two authors. These occurred at operating pressures between 2.8 and 3.6 bars (dotted lines in *Figure 6*), which is not too different from the measured Pc values.

Consequently, hydrostatic S4 test results of uPVC water pipes seem more closely related to practical conditions than S4 tests on PE or PA pipes.

Tensile Impact tests

The T_{bd} values in the Tensile Impact Tests on the gas pipes are slightly (R is only 0.55) influenced by the year of installation (Figure 7).

One can also perform an alternative statistical evaluation by calculating the average T_{bd} for the pipes installed from 1960 through to 1970 and the average T_{bd} for the pipes installed in or after 1972 (*Figure 7*). Using Student's t-test [18] it was assessed that the differences between the two installation periods are statistically significant.

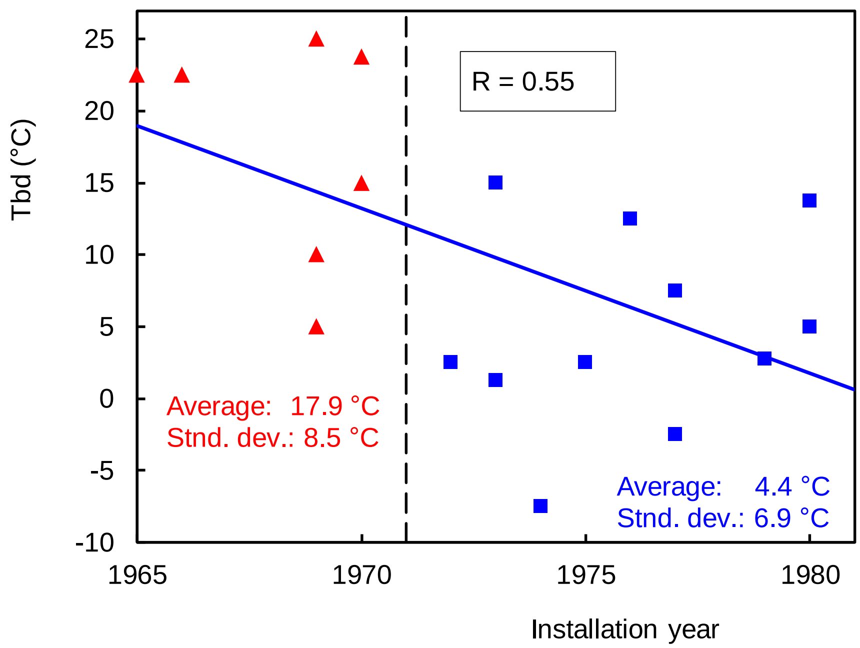

Figure 7. The 32 and 110 mm gas pipes that were installed after 1970 tend to show a lower (better) brittle-ductile transition temperature. The Student t-test on these two populations shows that these differences are statistically significant (P = 0.002).

There are two possible explanations for this:

1. A reduction in impact resistance could occur due to slow ageing in the soil.
2. The initial quality of the pipes installed in and before 1970 was lower than that of the pipes installed in and after 1972. Starting in 1972, chalk was added to about 50% of the investigated pipes and this improves not only the stiffness but, depending on the particle size, also the resistance to impact [21,22]. Newer pipes have also been produced using improved extruders, for instance with a higher length/diameter ratio, which provide a better mixing of the melt and hence produce a more homogeneous pipe quality. A conversion from emulsion to suspension uPVC took place around that time as well [20]. Also, the degree of gelation was gradually better kept in control.

Explanation 2 is the most likely one. Moreover, explanation 1 can be disproven as follows.
Firstly, the Pc in the RCP test shows no negative influence of further ageing (*Table 3*).
Secondly, Figure 8 shows results of Tensile Impact tests on test bars, taken from three different installation years after various ageing times at 50 °C, for up to 256 hours. These is additional test

data from Netherland. In none of the cases there is any influence of ageing, because R is much too close to zero.
These findings prove that the differences in Figure 7 are not due to ageing, but governed by the initial pipe quality. This confirms previous results obtained by *Alferink et al* [20], who also concluded that for uPVC pipes initial quality is the most important determinant factor by far.

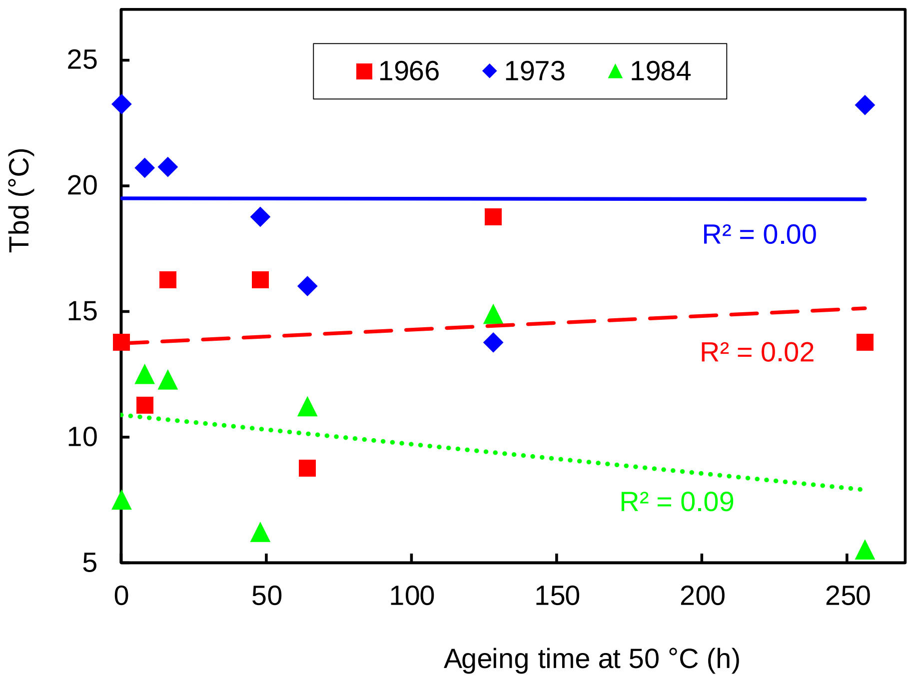

Figure 8. T_{bd} of three types of excavated uPVC gas pipes from Netherland, with various installation years, versus the time of oven ageing at 50 °C.

A note of caution is given here.
The measured T_{bd} values should not be directly compared with practice. T_{bd} is measured on test bars and should be used in a comparative manner, rather than as an exact value to describe the situation of whole pipes buried in the ground. The impact speed in meters per second and the magnitude of the impact force are also very important, as well as how tight the soil surrounding the pipe is compacted [27].

A second note of caution is related to *Figure 3*, which shows that brittle behaviour in the tensile impact test at a low soil temperature coincides with a reduction in the mechanical impact energy from about 750 to about 300 J/m^2. This is a reduction by 40 % of the value for ductile fracture, but definitely not down to zero. This means that, even at low temperatures, the pipes will not fail spontaneously in the soil, but only after a considerable mechanical impact by a third party.

CONCLUSIONS

1. The excavated uPVC pipes still meet the requirements of the modern standard EN 1452 regarding dimensions, time to failure in Hydrostatic Pressure (HP) tests at 20 and 60 °C and K-value. A few pipes show an exception with a slightly elevated frozen-in stress in the axial direction or a slight out-of-roundness, but their mechanical properties were not affected.
2. The investigated 110 mm SDR21 uPVC water pipes are highly resistant to Rapid Crack Propagation (RCP) at 3 °C. The Critical Pressure Pc for RCP is 5.75 – 8.25 bar. This is much

higher than for pipes with a thinner wall, such SDR26, SDR34 and SDR41 pipes. The reason for the high resistance in this test is that all pipes investigated in the present project have a thick wall (SDR21). Those countries that use thin-walled uPVC water pipes may encounter more RCP cases in practice than those countries that only use thick-walled uPVC pipes.

3. When soil temperatures fall, the resistance of the investigated uPVC pipes against impact failure is still adequate to prevent any spontaneous failures. Large third-party impact loads will be needed to inflict any failures.
4. The pipes installed from 1960 through to 1970 show – on average – a slightly lower resistance in the Tensile Impact test. This is not due to ageing, but due to a poorer initial quality, typical for that era. This is consistent with the findings of other authors.
5. The cooling (Janson) stresses lead to a slight reduction in the time to failure in the HP test at 20 °C and also decrease the results of the tensile impact test, but stresses in axial direction do not. Therefore, measuring cooling stresses cannot be replaced by measuring axial stresses.
6. The investigated uPVC pipelines can still be used during several decades to come.

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