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THE QUALITY OF OLD AND NEW PE PIPES USING PENT AND CPENT TEST

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SHORT SUMMARY

To gain an insight into the residual quality of first-generation polyethylene (PE) pipes used in the Dutch gas distribution grid, pipe segments from all over the Netherlands were excavated by the DSOs and tested by Kiwa Technology. The residual quality was determined using the PENT test. This study compared the PENT test with the CPENT test. Pipe material was also artificially aged using hydrostatic pressure at an elevated temperature and subsequently tested using the PENT and CPENT tests. Microscopic images were taken of the fracture surfaces to evaluate the results in greater detail.

KEYWORDS

first-generation PE, pipe material, residual quality, PENT, CPENT.

ABSTRACT

To gain an insight into the residual quality of first-generation polyethylene (PE) pipes used in the Dutch gas distribution grid, pipe segments from all over the Netherlands were excavated by the Dutch Distribution System Operators (DSOs) and tested by Kiwa Technology. The residual quality was determined by performing the Pennsylvania Edge Notch Tensile (PENT) test in accordance with ASTM F1473/ISO 16241. The test specimens were taken directly from the pipe segments. However, this test is not practical for the latest generation of polyethylene grades (including PE 100-RC and PE 4710 PLUS), as the testing time would be impractically long [1]. The Cyclic Round Bar (CRB) test method carried out in accordance with ISO 18489 can solve this problem. A correlation with the PENT test has also been shown [2]. The wall thickness of many pipes is too thin to produce suitable test specimens. In this situation, the Cyclic PENT (CPENT) test is a practical alternative. This test method combines the PENT specimen shape with the cyclic loading used in the CRB test. This method was introduced by Deakin University in Australia in 2018 [3] [4].

This study compared the PENT test with the CPENT test. Multiple (old) pipes were tested using the PENT test and CPENT test. The failure time for the PENT test was then compared to the cycles to failure for the CPENT test.

Pipe material was also artificially aged using hydrostatic pressure at an elevated temperature and subsequently tested using the PENT and CPENT tests. The failure time and cycles to failure decreased due to artificial aging (hydrostatic pressure at 3 MPa and 80 °C for 800 hours). This confirms that both tests can be used to assess the reduction in residual quality.

Microscopic images of the fracture surfaces were taken to allow the results to be evaluated in greater detail. Optical microscopy was used to distinguish different zones, including a surface cut with a knife, which was the initial crack from the notching, a smooth region, which represented the slow crack growth (SCG) during the test, and a rough zone where the final (rapid) fracture occurred. The stress increased as the surface area decreased during the test. This resulted in a ductile fracture. These zones could be found on the specimens from both the PENT and CPENT tests. The elongation of the test specimens during both the CPENT tests was also studied.

INTRODUCTION

Polymer pipes have been widely used in the Dutch gas distribution grid since the 1960s. There are currently around 21,000 km of polyethylene (PE) pipes in the ground that carry gas at pressures of up to 4 bar. From an asset management perspective, it is important to understand the quality of the individual pipes and to gain an impression of how the quality decreases over the years.

To gain an insight into the residual quality of first-generation PE pipes used in the Dutch gas distribution grid, pipe segments from all over the Netherlands were excavated by the Dutch Distribution System Operators (DSOs) and tested by Kiwa Technology. The residual quality was determined by performing the Pennsylvania Edge Notch Tensile (PENT) test in accordance with ASTM F1473/ISO 16241. The test specimens were taken directly from the pipe segments. However, this test is not practical for the latest generation of polyethylene grades (for example PE 100-RC and PE 4710 PLUS), as the testing time would be impractically long [1]. This shows that while the quality has improved greatly since the first materials came onto the market, we have lost the ability to assess quality differences and identify trends that arise in the ground over time.

The Cyclic Round Bar (CRB) test method carried out in accordance with ISO 18489 can solve this problem. A correlation with the PENT test has also been shown [2]. However, the wall thickness of many pipes is too thin to produce suitable test specimens. In this situation, the Cyclic PENT (CPENT) test is a practical alternative. This test method combines the PENT test specimen shape with the cyclic loading used in the CRB test. This method was introduced by Deakin University in Australia in 2018 [3] [4].

EXPERIMENTAL

In this study, we compared a well-established test (the PENT test) with a newer test (the CPENT test). Both tests assess slow crack growth in PE materials, which is the dominant cause of long-term PE pipe failure. A well-established data set for PENT tests carried out on pipes excavated from the Dutch gas grid is available. The pipes were manufactured and installed in the 1960s and 1970s and had been in the ground for a long time. They had been used at various pressures of up to 4 bar. This means there are differences in both production quality and degradation over time. The details of each individual pipe are not always known.

Various parameters affect the test results, including the initial quality (both material and extrusion) and degradation due to environmental effects and internal pressure. Because there was only one test result for the degradation over time of each material, the effects had to be evaluated using different materials. The measured materials were registered as first-generation pipes. However, some pipes showed PENT test values that indicated that they were made of newer materials. This was sometimes confirmed by the construction year. In other cases, these discrepancies occurred due to registration errors in data recorded over 40 years ago.

For comparison a pipe material was artificial aged, which consisted of applying a hydrostatic pressure of 3 MPa at 80 °C for different time periods. The objective was to determine whether it is possible to measure degradation.

The PENT test is a creep test carried out using a notch specimen that has been taken from a pipe. The specimen is taken from the axial direction of the pipe and has a width of 25 mm and a thickness equal to the wall thickness of the pipe. Notches of 1 mm are created on both sides of the specimen. The main notch is in the inner wall of the original pipe. The depth of this notch varies depending on the wall thickness. The specimen is subjected to a stress, which in this case was 1.5 MPa, at a temperature of 80 °C. This resulted in a stress intensity factor (Ki) of 0.3 MPa $m^{0.5}$. A total of five specimens were tested and the average time to failure was determined.

The CPENT test uses the same specimen, but in this case it is dynamically loaded. The specimen is subjected to a continuous tensile load. A sinusoidal load cycle with a load ratio of 0.1 is performed, which means the full load is nine times higher than the lowest part of the cycle. The cycle has a frequency of 10 Hz and is performed at room temperature. A total of four specimens were tested at different stress intensity ranges (ΔKi). The CPENT results were evaluated at a ΔKi of 1.75 MPa $m^{0.5}$ to allow a comparison to be made with the failure time of the PENT test.

Calculation of the stress intensity factor range (ΔKi):

$$\Delta Ki = (\Delta\sigma)\sqrt{\pi a}\left[1.12 - 0.23\left(\frac{a}{b}\right) + 10.56\left(\frac{a}{b}\right)^2 - 21.74\left(\frac{a}{b}\right)^3 + 30.42\left(\frac{a}{b}\right)^4\right] \text{ [5]}$$

PENT

The failure times ranged from 0.25 hours to 586 hours, as can be seen in figure 1. The PENT test failure times thus indicate large differences in quality, although these may be due to either the initial quality or degradation over time. Although the failure times were low, the pipe quality is adequate for the working pressure in the Dutch gas grid. The PENT test failure times for the first-generation materials do not correlate to the duration of use, which varied from 20 to 60 years.

In addition to the PENT test, a pipe material was artificially aged to gain an insight into the degradation process and to determine whether degradation can be measured. The aging consisted of applying an internal hydrostatic pressure of 3 MPa at 80 °C. Measurements were made using the PENT test after 0, 125, 250 and 500 hours on a pipe that had been excavated from the ground after 44 years of use. The artificial aging was converted into a duration of use using internal pressure values from Hoechst pipe material [6] by applying the Popelar shift method [7]. This is indicated by the green line. This method converts the 125, 250 and 500 hours of artificial aging into 10, 20 and 40 years of use at a hoop stress of 6 MPa. This represents a worst-case scenario compared to the stress caused by the working pressure in the Netherlands. The results are shown as orange points in figure 1. The fit is indicated by an orange line. Although the artificial aging was performed on only one material and does not necessarily apply to other pipe materials in this population, it does give an indication of how first-generation pipe materials have degraded over time.

Figure 1 shows that the effect of extensive artificial aging on an excavated material is much smaller than the differences in quality that we see in the population. It is likely that the other excavated materials in the population would show similar results. The population consisted of materials that had been in use for 20 to 60 years. However, the duration of use and the resulting degradation did not show a significant correlation with the PENT test failure time. It is unlikely that this is because we are unable to measure degradation caused by long-term use, but rather because of the large differences in initial quality, which we could not control for as we tested excavated pipes. This leads us to the conclusion that the current quality is primarily dependent on the initial quality.

However, the results do show that we can use the PENT test to measure degradation, as the test with the artificially aged pipe shows.

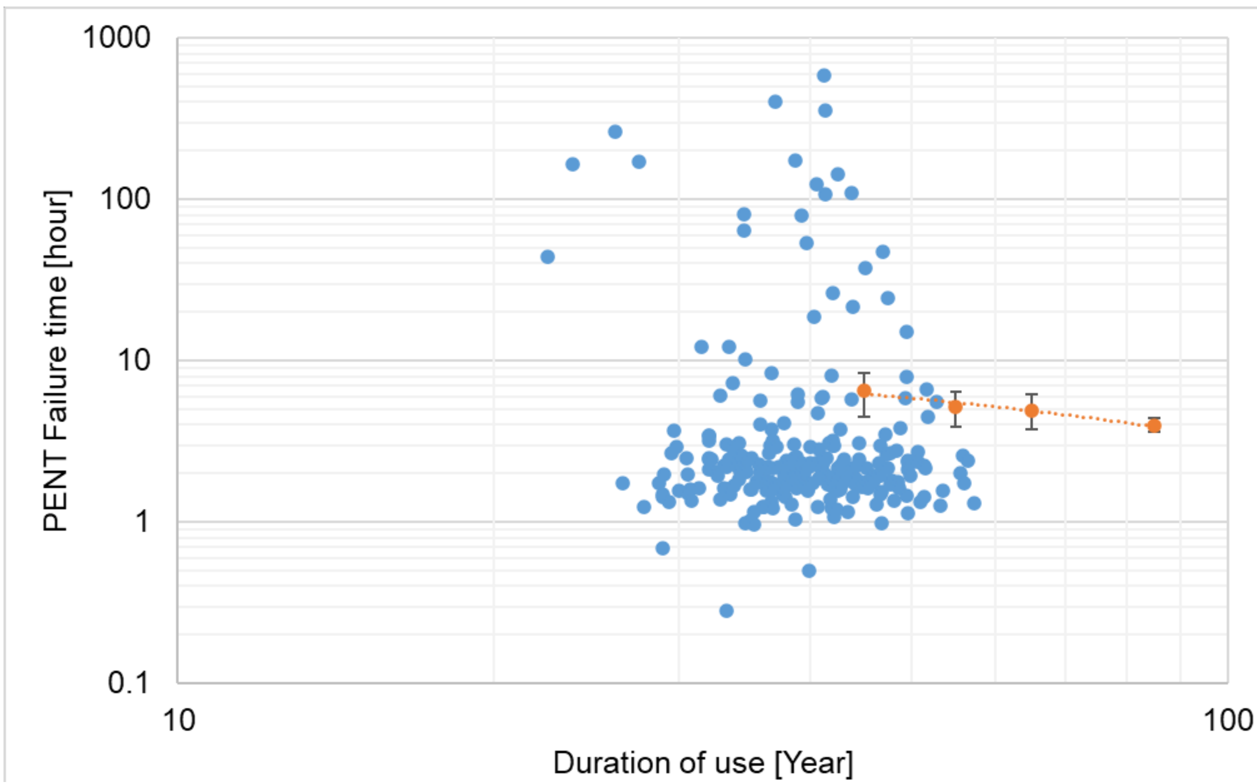

Figure 1. PENT failure times of tested pipes and PENT failure times of an artificially aged pipe.

Surface pressure and pipe wall stress

The grid consists of pipes that carry a range of pressures and that have various wall thicknesses and diameters. These differences resulted in differences in stress in the pipes that were tested. As the stresses in the pipe wall differ, different degradation should occur and thus differences in failure times for the PENT test should arise. These can be seen in figure 2. We only have one data point, i.e., after the pipe was excavated. This means we cannot make a direct comparison. We can conclude from this that the pipes that were subjected to a higher stress during use have shorter failure times.

The statistical tests with Kendall's tau b [8] and Spearmann's Rho [9] [10] indicated that the correlation is significant, with a confidence of 95%. A one-tailed test was chosen in this case because it was assumed that any relationships have a direction, for example a higher pipe pressure will result in a lower PENT test failure time.

In this case, a selection of pipes was taken from pipes that had PENT test failure times under 13 hours. We can be confident that these were first-generation pipes and exclude second-generation which behave differently.

Both methods use the ranking numbers of the data rather than the actual data. The method ranks the data according to the value of the variables examined. The tests consider whether the data ranking is the same for the two variables being compared. These may be based, for example, on the pipe pressure and the results of the PENT test. For example, if the ranking based on the PENT test failure times is comparable to the ranking based on the stress in the pipe wall during use, then there is a correlation. No significant correlation was found for other factors, such as construction year, soil type, diameter or surface structure (visual inspection).

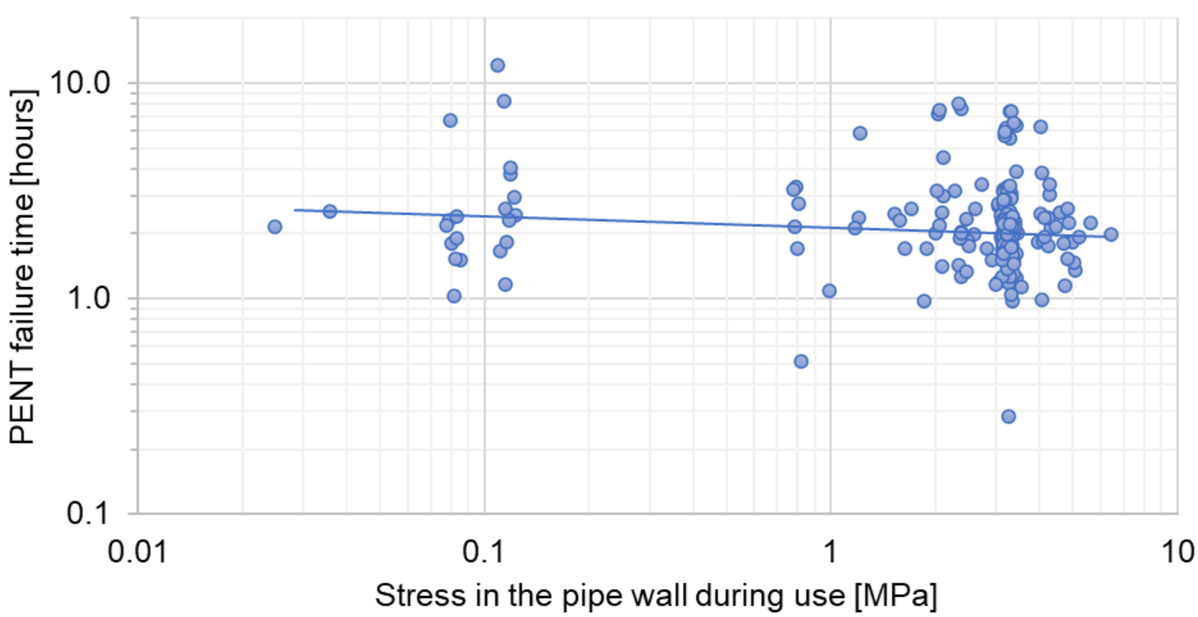

Figure 2: PENT test failure times and the stress in the pipe wall.

CPENT

The CPENT test was used to test 15 materials. For each material four specimens are tested of which a fit is made. The results are shown in figure 3. Figure 4 shows the results of the CPENT test for a pipe material that had been artificially aged for 800 h compared to the original material. The results allow a comparison to be made between two test series, each of which consisted of four specimens. This indicates that the artificial aging process can be measured. Further research is required to confirm this.

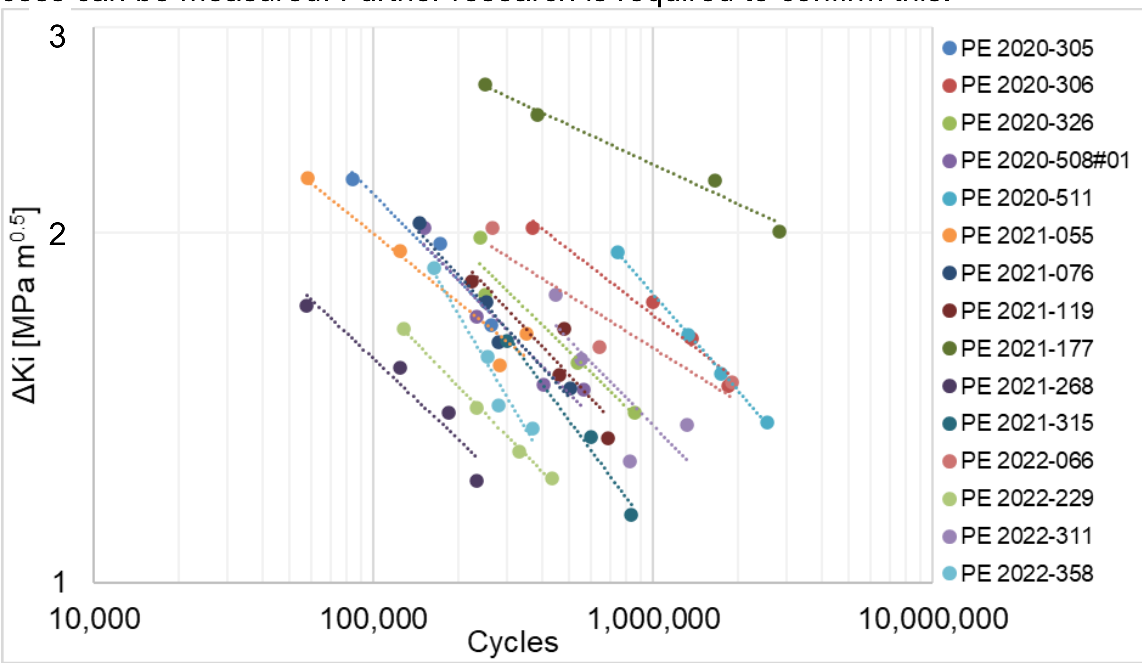

Figure 3: CPENT test failure cycles vs. stress intensity (ΔKi). The dotted line shows a fit between the four tested specimens.

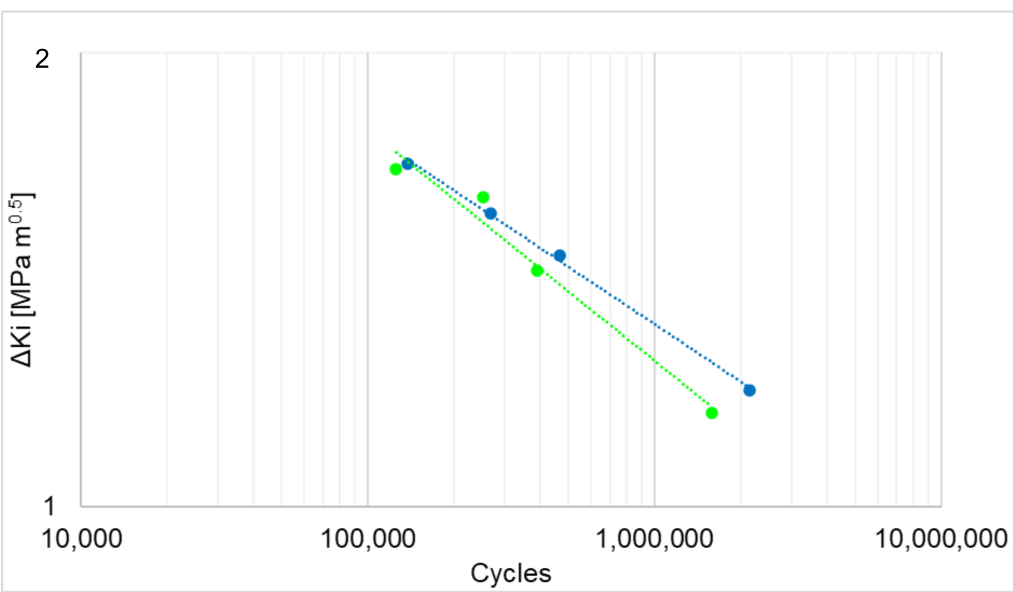

Figure 4: CPENT test failure cycles vs. stress intensity (ΔKi) for a pipe material in blue and the same pipe aged for 800 hours in green.

PENT AND CPENT CORRELATION

Error! Reference source not found. shows the results for both the PENT test failure time and the CPENT test cycles at a Ki of 1.75 for 15 materials. The red data point represents a second-generation material that did not fail during the PENT test. In some cases, the evaluation point for a Ki of 1.75 falls outside the measured range for the CPENT test then the cycles at a Ki of 1.75 are extrapolated rather than interpolated. This results in an unrealistic value and is shown only for comparison.

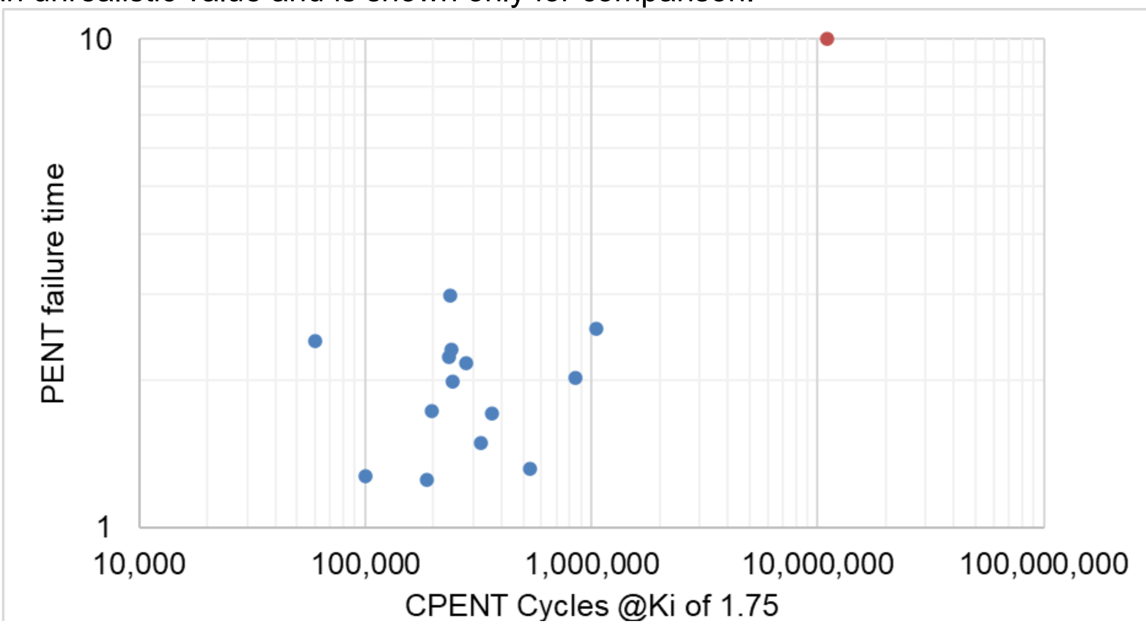

Figure 5: PENT test failure time vs. CPENT test cycles @Ki of 1.75. The red data point represents a second-generation material that did not fail during the PENT test.

The results were evaluated in greater detail using optical microscopy on the fracture surfaces. Different zones were distinguished, including a surface cut with a knife, which was the initial crack from the notching, a smooth region, which represented the slow crack growth (SCG) during the test, and a rough zone where the final (rapid) fracture occurred (see figure 6). The stress increased as the surface area decreased during the test. This resulted in a ductile fracture. The different zones could be found in the specimens used in both the PENT and CPENT tests.

Different observations were made for the PENT and CPENT tests. In some cases, an observation was made for either the PENT or CPENT test, while in other cases the observation was made for both tests. While similar fracture surfaces were observed for both the tests in most cases, the CPENT test seemed to show ‘cleaner’ surface areas.

No correlation was found between the ranking of the materials and the surface areas. Outliers in the test results could not be attributed to abnormalities in the surface areas.

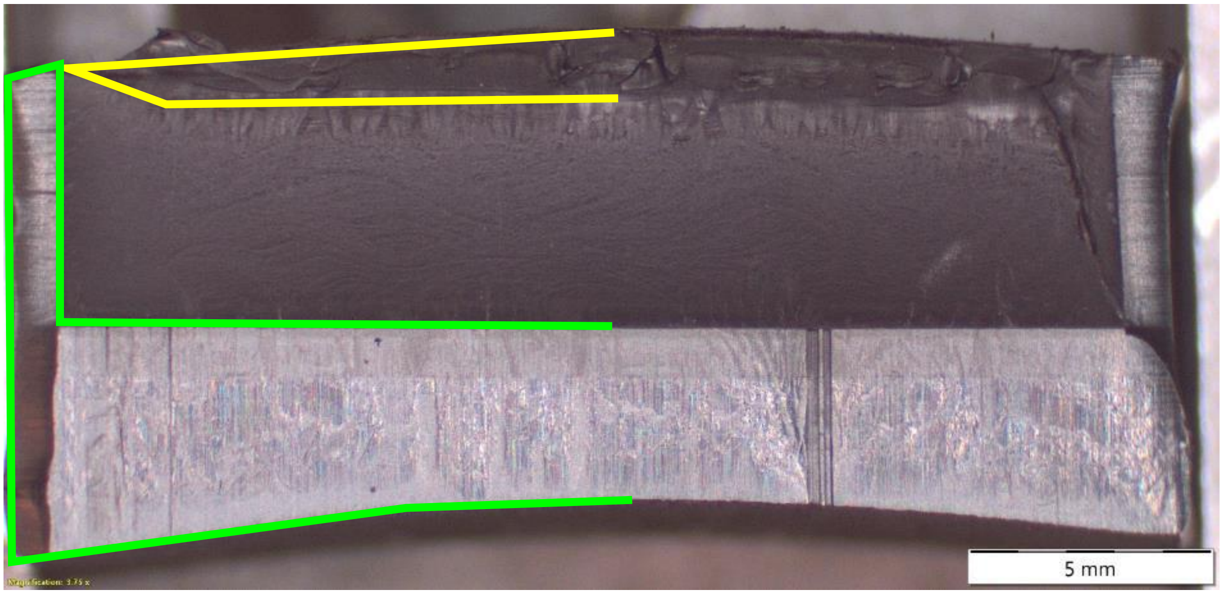

Figure 6: CPENT test fracture surface for PE 2022-229#2. The notch made with a razor blade is shown in green. The final ductile fracture is shown in yellow. The area in between is the smooth surface, which represents slow crack growth.

Contrary to the preciously sometime the fracture surface was disorderly (see figure 7). The different SCG phases as mentioned before were difficult to distinguish.

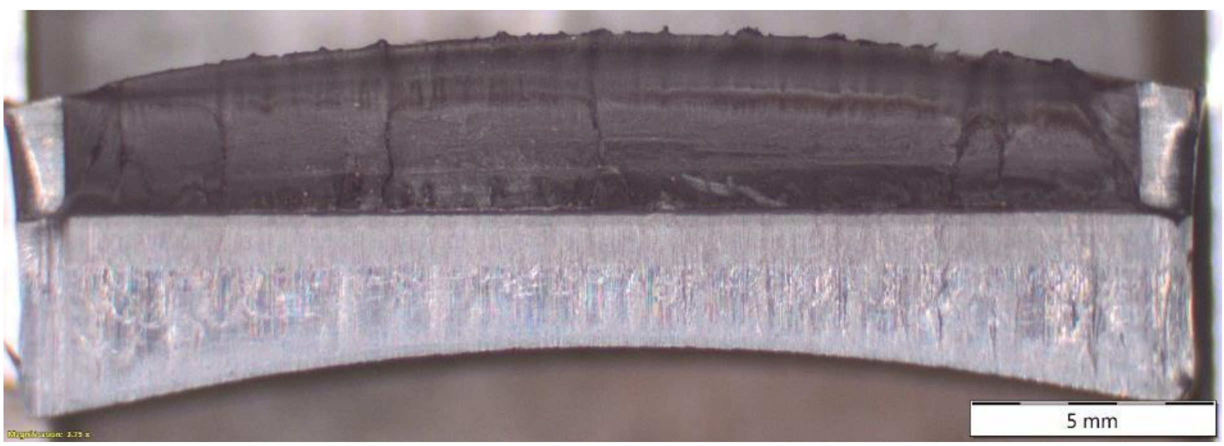

Figure 7: CPENT test fracture surface for PE 2022-311#3. The different SCG are difficult to distinguish.

In some cases, the SCG area fracture surface for both the PENT and CPENT tests showed distinct semicircular zones. These seemed to be distinct initiation areas, as they appeared to grow from the notch to the ductile area. Where these were identified in a material, they appeared for both tests. figure 8 shows an example with four distinct zones.

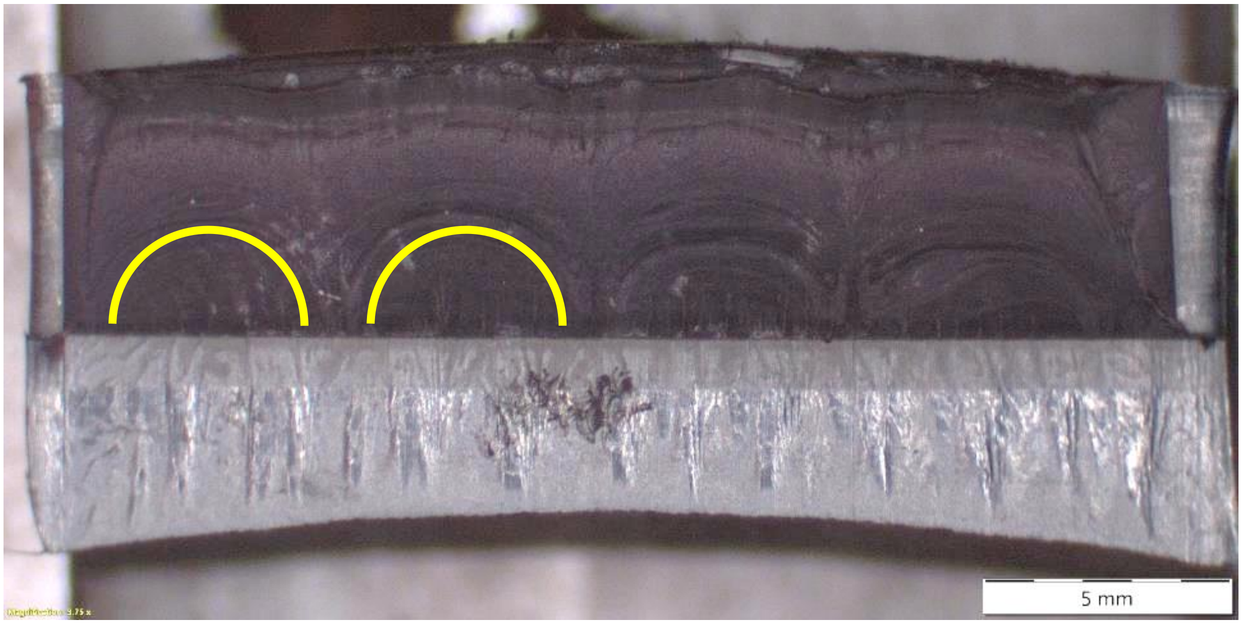

Figure 8: CPENT test fracture surface of PE 2021-268#4. Four semicircular zones can be distinguished. These appear to be distinct initiation points. Two of the four zones are indicated with yellow semicircles.

In many cases, the PENT test fracture surfaces showed distinct lines. These extended from the SCG area into the ductile area and probably arose during the final ductile fracture formation due to the surrounding PE being pulled towards the outside of the specimen. An example is shown in Figure 9.

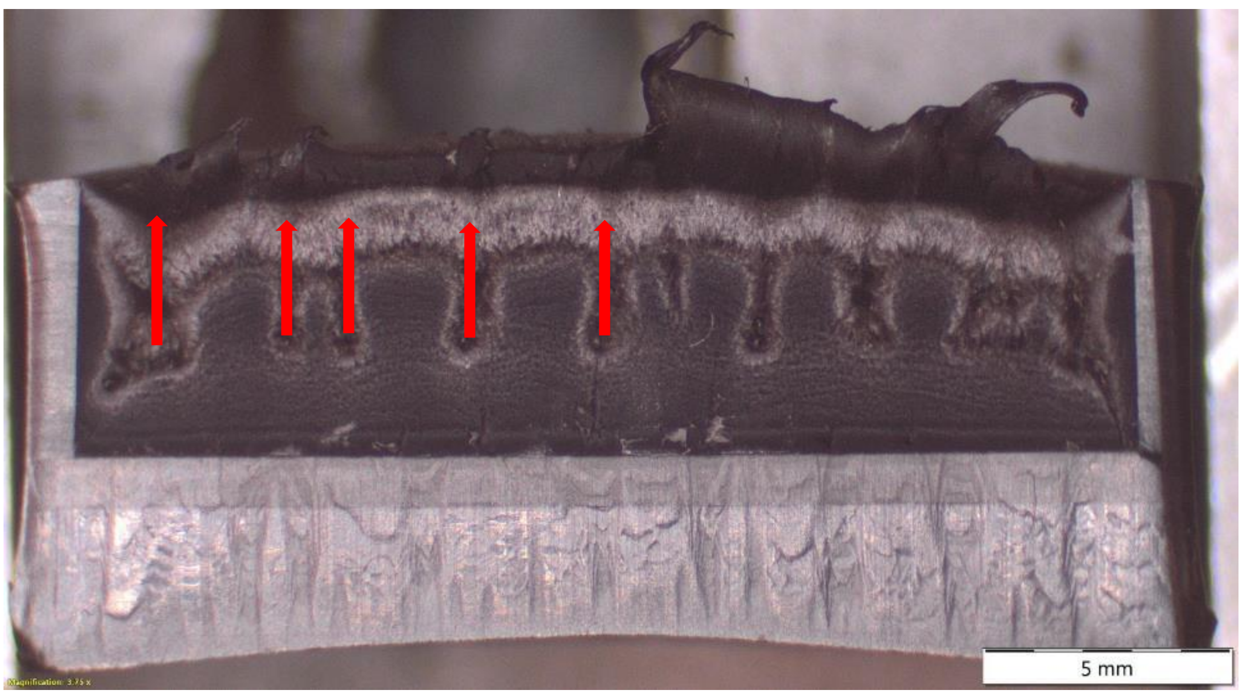

Figure 9: PENT test fracture surface of PE 2022-229#1. Lines can be distinguished. These are indicated with red arrows and probably arose during the formation of the ductile fracture.

For the CPENT the tensile displacement verses time curve until failure was studied. These are distinguished in two groups; the curve showing a smooth increasing slope and the curve showing a step during the test. For PE 2022-311 specimen 1 had a low ΔKi, large failure cycles, a smooth fracture and a smooth displacement curve versus specimen 4 which has a higher ΔKi, lower failure cycles, a disorderly fracture surface and a step in the displacement curve (see figure 10). This kind of relationship was not found for most other tests. An overview with all summarized findings can be found in table 1.

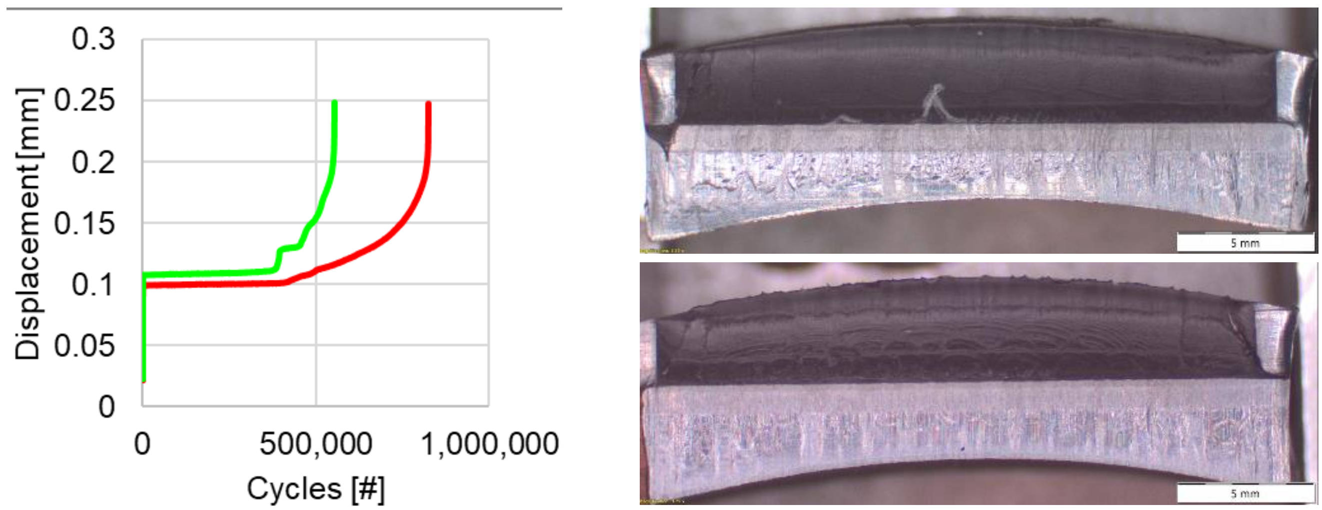

Figure 10: Left the displacement vs cycles of CPENT PE 2022-311. #1 in red and #4 in green. On the top right the fracture surface for #1 and bottom right for #4.

Table 1: Overview of all the findings; PENT failure time [h] and the fracture surface, CPENT cycles @Ki 1,75 the fit (R^2) and the fracture surface and an evaluation of the displacement curve.

	PENT failure time [h]	PENT std [h]	Fracture surface	CPENT cycles @Ki 1,75	CPENT R^2	Fracture surface	Displacment
PE 2020-305	3.0	0.9	Semicircles	235965	0.95	Semicircles	Smooth
PE 2020-306	2.0	0.4	Disorderly	852058	0.97		Steps
PE 2020-326	1.5	0.6	Semicircles	325020	0.92		Steps
PE 2020-508	2.2	0.4		235657	0.92		Steps
PE 2020-511	2.6	0.7		1044628	1.00		Steps
PE 2021-055	1.7	0.3	Disorderly	195934	0.93	Disorderly	Smooth and steps
PE 2021-076	2.0	0.2		241772	0.95		Steps
PE 2021-119	2.2	0.3		279437	0.82		Smooth
PE 2021-177	No failure			11052729	0.98		Smooth
PE 2021-268	2.4	0.4	Semicircles	59778	0.93	Semicircles	Smooth
PE 2021-315	2.3	0.1	Semicircles	240770	0.98	Semicircles	Smooth and steps
PE 2022-066	1.3	0.1		531016	0.87		Smooth and steps
PE 2022-229	1.3	0.2		100038	1.00		Smooth
PE 2022-311	1.7	0.4	Disorderly	361987	0.64	Disorderly	Smooth and steps
PE 2022-358	1.2	0.1	Disorderly	187130	0.95	Disorderly	Steps

CONCLUSIONS

This research shows that both the PENT and CPENT can be performed on pipes that have been excavated from the ground. These pipes are produced a long time ago, the exact initial quality is unknown and the exact degradation history is unknown. Using test results after 20 to 60 years of use no correlation was found between the PENT and CPENT while both evaluate the resistance to slow crack growth. Both test do show a sensitivity to degradation as a result of artificial aging.

A large data set was build for excavated pipes using the PENT. Using this dataset a correlation was found between the working pressure and PENT failure time. This gives us confidence that we can build comparative quality assessment for first-generation pipes in the gas distribution grid.

ACKNOWLEDGMENTS

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