A Model to Predict Rapid Crack Propagation in PVC Water Pipes

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Abstract

Very occasionally PVC-U water pipes suddenly fail due to a long brittle crack with a length of many meters which propagates with the speed of sound along the pipe and causes extensive water loss. This phenomenon was recognized as Rapid Crack Propagation (RCP). Conditions for the occurrence of RCP are an operating pressure above the Critical Pressure (P_C) combined with a sudden pressure surge or water hammer which initiates the crack. Laboratory measurements on 25 pieces of water-filled 2.42 m long, 315 mm pipe segments according to ISO 13477:2008 were performed at 3 °C to assess how P_C depends on the wall thickness. For water-filled pipes a thicker pipe wall clearly increases the resistance to RCP, but residual pipe extrusion stress has a distinct negative influence. A multivariate statistical model was developed which describes these influences quantitatively which can be used to calculate whether RCP is possible or not.

Introduction

Unmodified polyvinylchloride (PVC-U) pipes are used successfully by water distribution companies in Netherland for drinking water pipelines. On average 51% of the total pipeline length is made of PVC [1]. The oldest PVC pipelines date back to the late 1950s. The track record of PVC-U water pipes is good and several old PVC-U pipelines have exceeded their design life of 50 years. The question has arisen if they can be kept in operation for longer.
This can only be assessed if the most important failure mechanisms – apart from third-party damage – are understood. When pipeline quality is only based on failures due to Slow Crack Growth (SCG) a lifetime expectancy of another 30-50 years seems possible [2].
If SCG occurs typical crack growth rates are low, in the order of 0.1 to 1 mm per year.

However, in the last five years the water distribution sector has realised that in addition to SCG another failure phenomenon, which has often been overlooked, may occur as well. In some PVC pipes sudden longitudinal brittle fractures with a length of many meters have occurred (Figure 1 and Figure 2). This is known as Rapid Crack Propagation (RCP).
So far, at least 30 cases of RCP in PVC-U water pipes and fittings were noted in Netherland since 2003, although data from several water distribution companies is not yet available. Such failures were partly due to pressure surges or water hammer and partly because SCG had already led to a minute pre-existing defect in the pipe wall. Although not many cases of RCP occur, the consequences are significant, because of the massive water loss.

The propagation speed of an RCP crack in a water-filled PVC pipe can reach 600 m/s [3].
Obviously, the pressure quickly falls off but in water-filled PVC pipes this decompression speed is lower, typically 450 m/s [3]. Consequently, the decompression speed cannot keep up with the crack propagation speed. This means that once an RCP crack in a water-filled PVC pipe is created there is nothing to stop it until a mechanical joint is reached, where an RCP crack always stops, but not at a butt-fused joint [4].
The difference in crack propagation speed compared to SCG cracking speed is huge. Another difference is that an RCP crack propagates into areas well beyond the initiation site.

Figure 1. PVC water pipe with a long brittle crack due to RCP.

Figure 2. Water flows out after RCP in a PVC water pipeline.

At such distances propagation follows physical laws unrelated to the conditions at the initiation site. However, SCG behaviour remains related to the initiation site at all times. Local stress concentrations (due to a small inclusion in the material or a point load) enhance crack initiation, but the SCG rate decreases when the crack approaches the boundary of the stress concentration area. For water pipelines this means that SCG causes small controllable leaks whilst RCP leads to large cracks and uncontrollable water losses.

When a pipeline suffering from RCP runs in the countryside, under a road verge or pavement, the consequences may be limited. However, when a pipeline is located in sensitive areas, like close to a motorway, railroad, dyke or underground station the consequences may be more serious. In Germany an underground car park with 60 cars was flooded due to RCP.

For lab testing, two ISO methods exist for measuring RCP in plastic pipes, the Full Scale (FS) test [5] which simulates the conditions in a long pipeline and the S4 (Small Scale Steady State) test [6] on segments with a length of only about 7 times the nominal pipe diameter. These standards define that RCP occurs when a fast brittle crack exceeds the critical crack length, which is 4.7 times the nominal diameter. The water pressure at which this occurs is the critical pressure (P_C). Below P_C crack arrest occurs. The ISO standard [6] defines P_C as the highest pressure at which arrest occurs, below the lowest pressure at which RCP occurs. The experiments described here aim to determine P_C at various SDR values (Standard Dimension Ratio: diameter/wall thickness).
It is important to realise that pneumatic RCP tests on air-filled pipes may be performed, but also hydrostatic tests on water-filled pipes, as in this publication.

Leevers and Greenshields [7-12] have shown that for water-filled PVC pipes the critical pressure in the FS test is the same as the critical pressure in the S4 test:

$$P_C\,(S4) = P_C\,(FS) \qquad (1)$$

although this is definitely not true for air-filled polyethylene and polyamide pipes [13,14].

Materials and Methods

Existing equipment for pneumatic S4 tests was converted to perform hydrostatic S4 tests on water-filled Ø315 mm PVC pipes, produced in 2010 and 2012 by a well-known Dutch pipe manufacturer. Twenty-five segments of 2.42 m length each were tested at 3 °C, being the lowest observed drinking water temperature in Netherland.

Pipes with three different wall thicknesses were tested: SDR26, SDR34 and SDR41. For each SDR value 3 pipes with a length of 10 m were cut in 12 segments each with a length of 2.42 m.

Each tested pipe segment was filled with a water glycol mixture at 3 °C and pressurised at a constant pressure between 1 and 5 bar (Figure 3). The crack was initiated using a sharp stainless steel knife (Figure 4). The width of the knife was 120 mm and the speed at which it hit the pipe was 11 m/s. No baffles [6] were applied.

Despite the extreme initiation method (prescribed in ISO 13477) no RCP occurs when the water pressure is below P_C, but above P_C the outcome is RCP. The crack length was not defined from the middle of the notch [6] but from the edge of the notch. The difference is 60 mm.

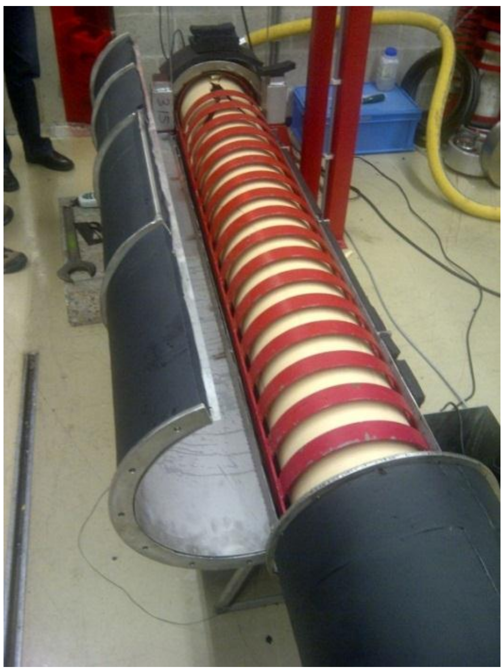

Figure 3. Test rig for hydrostatic S4 tests. Inside the PVC segment a water/glycol mixture flows to cool to 3 °C. Cooled air of 3 °C flows through the insulated steel jacket pipe (shown in open position).

Figure 4. Steel knife 120 mm wide which falls on top of the segment to initiate the crack. The knife was weighted to 36 kg. The width of the knife was aligned with the longitudinal direction of the pipe.

Results

Typical RCP behaviour is shown in Figure 5 and initiation resistance in Figure 6. Figure 6 shows two notches, because the knife bounced on the segment surface without initiating a crack. The intermediate phenomenon is arrest, the start of a rapid crack which stops before its length exceeds 4.7 times the diameter [6]. Arrest, a very common result with air-filled PVC pipes [15] and PE pipes, occurred only once in the 25 hydrostatic S4 tests.

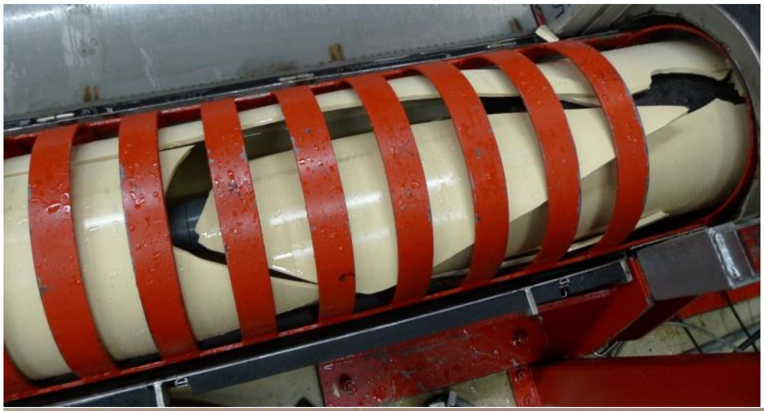

Figure 5. RCP after the S4 test above P_C on a water-filled 315 mm PVC pipe segment. The crack propagated further to the left, almost reaching the end of the segment (not shown).

Figure 6. External pipe surface of an "inert" segment without crack initiation. The knife bounced once thus creating a second smaller notch, also in axial direction.

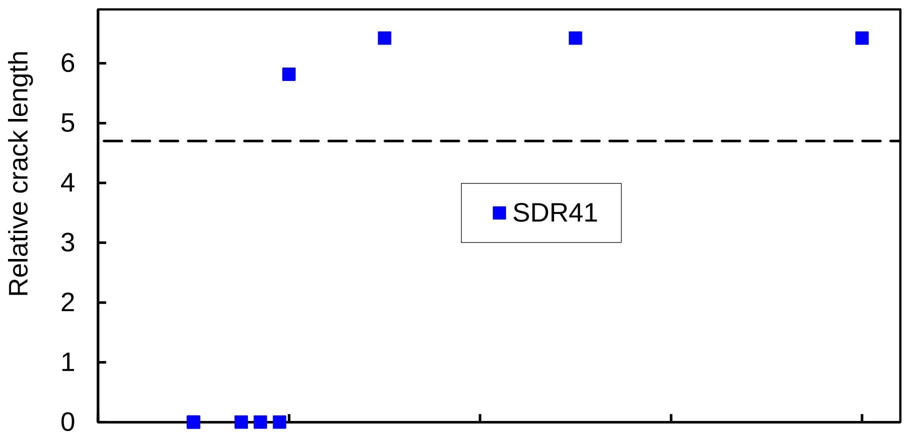

Figure 7. Relative crack length in the hydrostatic S4 test as a function of the water pressure in SDR41 pipes. P_C = 1,95 bar.

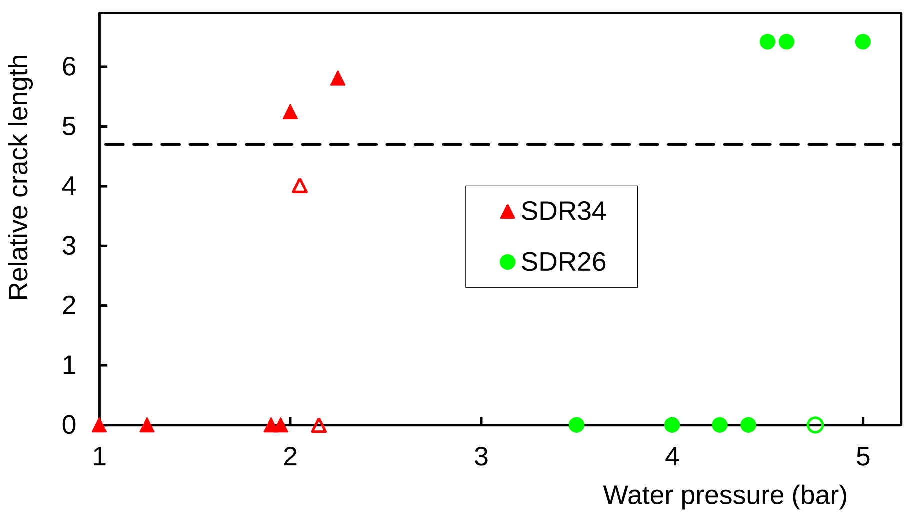

Figure 8. As Figure 7, for SDR34 and SDR26 pipes. Open symbols: to be removed from the P_C determination as prescribed by ISO [6]. SDR34: P_C = 1.95 bar, SDR26: P_C = 4.40 bar .

For water-filled PVC pipes the behaviour is almost binary: there is either no crack at all when the pipe pressure is below P_C or full RCP when the pipe pressure is above P_C. This is shown in Figure 7 and Figure 8 where the relative crack length (the crack length divided by the nominal diameter) is plotted as a function of the water pressure.

Figure 9 shows how P_C is influenced by the SDR. This Figure also shows P_C values calculated according to the method proposed by Leevers et al [7-12]. It was not investigated why these values are lower than the measured ones. Possibly the absence of baffles during the measurements plays a part. In both curves P_C decreases with SDR, i.e. P_C increases with the wall thickness, although the data point for SDR34 appears to be too low.

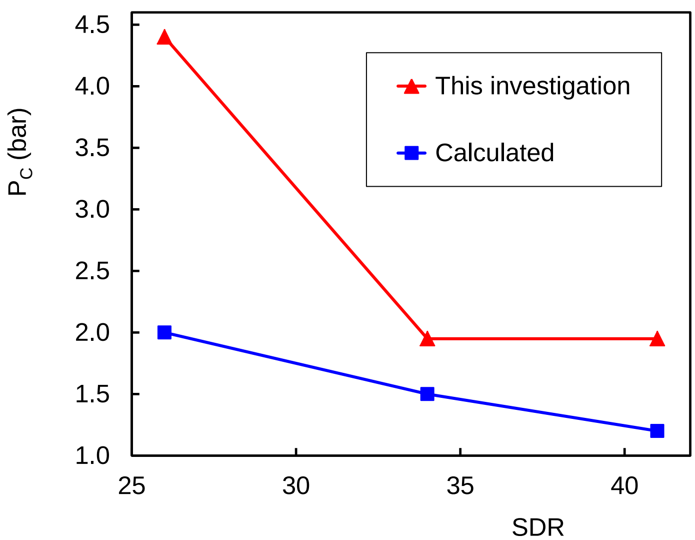

Figure 9. Influence of the SDR on the P_C of 315 mm PVC pipes in the hydrostatic S4 test and values calculated using the method proposed by Leevers et al [7-12].

Next it was investigated if the SDR34 pipes were in any way different from the SDR41 and the SDR26 pipes. Possible influences such as the degree of gelation, material composition, residual extrusion stress and the extrusion rate were measured.

Degree of gelation and composition

The degree of gelation was determined according to EN 1452, but with a different evaluation method, which specifies 4 gelation levels: very low, under gelled, optimally gelled and over gelled.

All investigated pipes (irrespective of their SDR class) proved to be over gelled, because none were attacked by dichloromethane at 15 °C. Over gelling leads to poorer impact resistance [16-19] compared with optimal gelation.

The compositions of the pipes were compared using infrared spectroscopy. No differences between pipes with various SDR values were noted.

Residual stress and extrusion rate

That PVC pipes contain residual stress is illustrated in Figure 10 and also by using the method of Janson [20]. A bar is cut in length direction from an intact pipe segment. The edges immediately move towards each other, quickly at first and later more slowly. Shrinkage of the circumference

(SC) after cutting was measured in pipes with various SDR values at regular intervals, up to 1,150 hours. The SDR34 pipes showed more shrinkage than the SDR41 and SDR26 pipes and hence had a higher residual stress (Table 1).

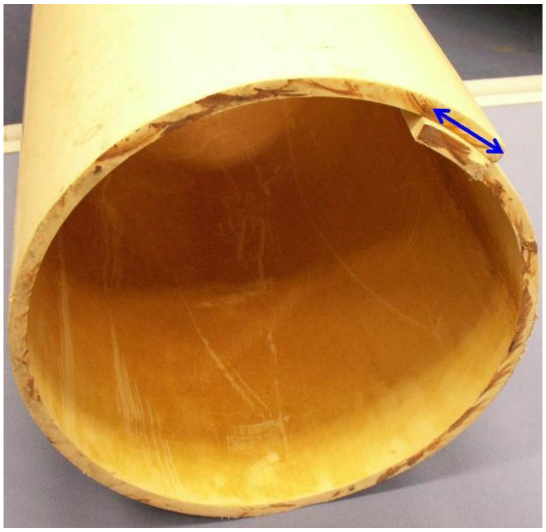

Figure 10. Overlap of the pipe wall (blue arrow) in tangential direction after RCP. From this overlap, or after cutting a bar in axial direction out of an intact pipe, the shrinkage in the tangential direction is calculated as a percentage (Table 1).

Table 1. Tangential shrinkage (1,150 hours after cutting a bar from pipes with three SDR values) and the extrusion rate.

SDR	Shrinkage of the circumference SC (%)	Extrusion rate (m/minute)
26	3.40	0.57
34	4.83	0.93
41	4.16	0.55

The extrusion rates of the pipes were determined from the time stamps on the pipe surface. The SDR34 pipes were extruded much faster than the SDR26 and the SDR41 pipes (Table 1). Possibly, the deviating SC value of the SDR34 pipes was caused by the higher extrusion rate.

Discussion

That the resistance of water-filled PVC pipes increases with increasing wall thickness (Figure 9) is an unexpected result. The general agreement in the field of pneumatic S4 tests is that the reverse is true. Two websites still mentioned this in 2013 and another still does. However, the calculations based on the method proposed by Leevers et al (Figure 9) confirm that for water-filled PVC pipes the RCP resistance increases with increasing wall thickness. This is a very important result, because it changes how RCP in PVC water pipes is understood.

Statistical model

A statistical (descriptive) model was developed to assess the influence of residual extrusion stress from the experimental data in Table 1, using the commercial software Sigma Stat ® [21].

SC was taken as a measure of the residual stress. Other variables in the model were the water pressure (P) and the SDR.
First the relative crack lengths in Figure 7 and Figure 8 were converted to logistic ones (binary values of 0 or 1). This was done by taking the maximum relative crack length (6.42 in the mentioned Figures) as a logistic value of 1. Some other values which were lower were rounded off to a logistic value of 1. These were one value at 2.0 bars in Figure 7 and three values at 2.0, 2.05 and 2.25 bar in Figure 8. The zero crack lengths did not need any conversion.

Equation (2) shows how the three variables govern the logistic crack length:

$$\text{Logit L} = a_0 + a_1 \,.\, P + a_2 \,.\, SDR + a_3 \,.\, SC \qquad (2)$$

Logit L is related to the logistic crack length L through equation (3):

$$L = 1 / (1 + \exp(-\text{Logit L})) \qquad (3)$$

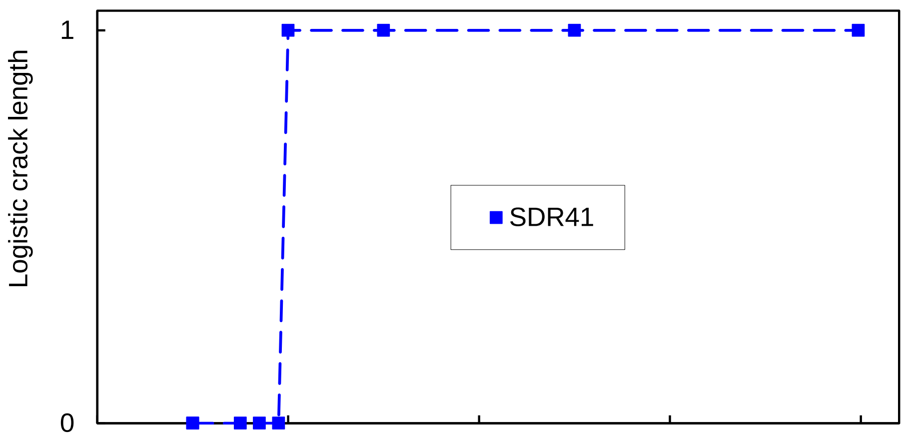

Figure 11. Description of the logistic crack length (L) of SDR41 segments with the statistical model. The same model with the same coefficients was used for Figure 12.

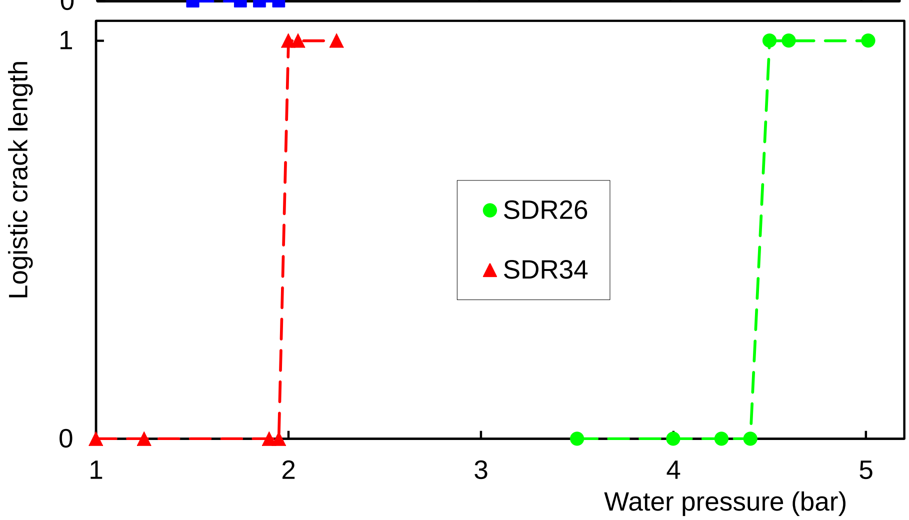

Figure 12. Description of the logistic crack length (L) of SDR34 and SDR26 segments with the statistical model, using the same coefficients as in Figure 11.

These combined equations form the statistical model. The software determined the best fit for all three SDR values together and this is shown in Figure 11 and Figure 12. The fit is very good. The values of a_0 until a_3 are known by the authors.

The statistical model also makes it possible to investigate the influence of residual stress (or SC in this case) on P_C separately. If it is assumed that the SC value of the SDR34 pipes is not 4.83 % as in Table 1, but the average of the SCs of the other two pipes (3.78 %), then a clear increase in the P_C of the SDR34 pipes is found (Figure 13). This indicates that a relative small decrease in the residual pipe stress already leads to a relatively large improvement (increase) in P_C.

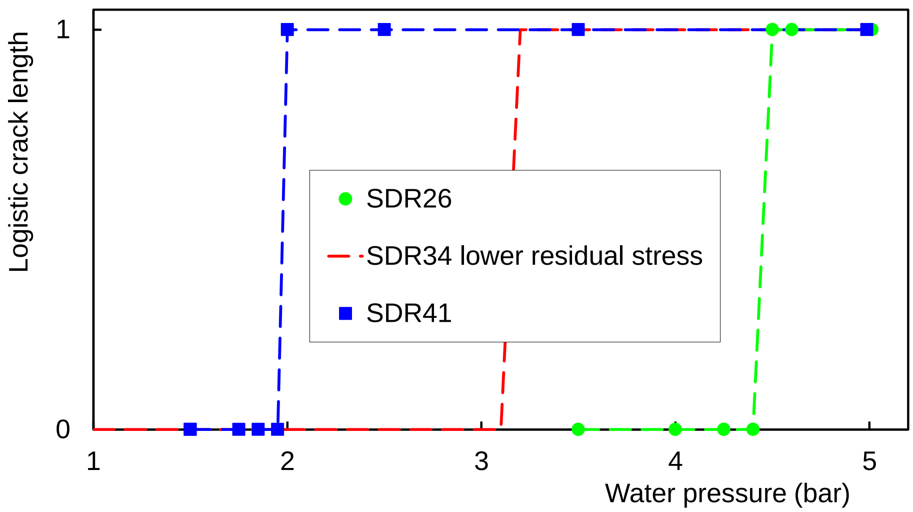

Figure 13. Prediction of the logistic crack length of SDR34 segments with the model, assuming a lower residual stress. Here, P_C increases from 1.95 to 3.1 bars. The curves of the SDR41 and SDR26 segments are not influenced.

Support for this finding was provided by pneumatic S4 tests on PVC pipes. These results were published earlier [15] and are reproduced in Figure 14 but with an additional test result of a segment that was tempered for 1 week at 50 °C to relax the residual stress.

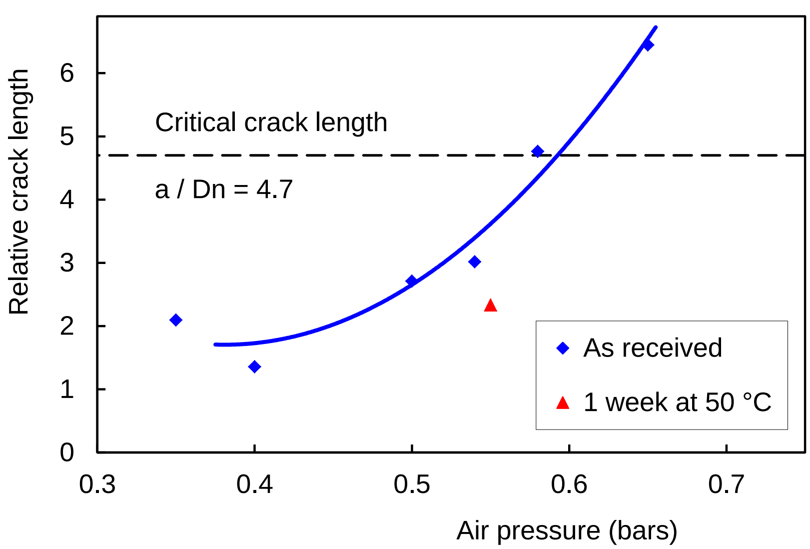

Figure 14. Relative crack length in the pneumatic S4 test as a function of the air pressure [15], measured on 315 mm SDR41 pipe segments at 0 °C. P_C in air is 0.53 bars at these pipe dimensions. The red point is from a segment in which the residual stress had been released by oven ageing during 1 week at 50 °C. There are five cases of arrest.

Obviously, this segment also went through a process of physical ageing which in itself would lead to a reduction in the impact resistance [22,23].
Hence, based on physical ageing alone, a lower P_C would be expected. However, the reverse is true, because the crack length decreases somewhat compared with the as-received pipes.
Hence, it appears the resistance to RCP increased somewhat. Apparently the effect of physical ageing is not large in this case and a more influential and opposite effect occurs. This effect is stress relaxation which proceeds relatively quickly at 50 °C. The residual extrusion stress is decreased by it which increases P_C. The results in Figure 14 thus support the finding for water-filled PVC pipes that decreasing residual extrusion stress increases the resistance to RCP (higher P_C).

Conclusions and recommendations

1. At 3 °C the P_C values found in this investigation (1.95 to 4.4 bars) for water-filled 315 mm PVC pipes lie in the normal operating pressure range for PVC water pipes in Netherland. Moreover, the results obtained with 2.42 meter long segments are also valid for longer pipes. This explains why since 2003 at least 30 cases of RCP have been observed in Netherland in PVC water pipes and fittings.
2. The behaviour of water-filled PVC segments is almost binary. At low water pressures, below P_C, the segments show complete resistance to any crack initiation, whilst above P_C full RCP occurs with a crack propagating almost through the entire segment length, up to the end cap on the other side. The reason is that the decompression speed of the water is lower than the crack speed in the PVC wall. There was only one case of arrest where a fast brittle crack that had already been initiated stopped before the critical crack length of 4.7 times the diameter was reached.
3. The wall thickness (SDR value) of water-filled 315 mm pipes has a large influence. P_C increases from 1.95 bars for thin-walled SDR41 pipes to 4.40 bars for thick-walled SDR26 pipes.
4. The risk of RCP fractures in PVC water pipes decreases by choosing a thicker pipe wall.
5. A second important variable is the residual extrusion stress in PVC pipes. This stress should be minimised to prevent a large negative influence on the resistance to RCP of water-filled PVC pipes.
6. It is advised to reduce the occurrence of water hammer and pressure surges in existing pipelines which are operated above P_C.

Further research

1. Bi-axially oriented PVC (PVC-O) sheet shows a resistance to impact loading which is 16 times higher than PVC-U sheet [24]. It is expected that the resistance to RCP of PVC-O pipes will also be higher than that of PVC pipes and this makes PVC-O pipes a very interesting new development.
2. Investigate the influence of higher water temperatures, other pipe diameters and the degree of gelation.

Acknowledgements

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