An Experimental Investigation into the Pressure Leakage Relationship of some failed water pipes

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Abstract

The results of pressure management field studies have shown that the leakage exponent is often considerably higher than the theoretical orifice value of 0.5. The first part of this paper identifies and analyses factors that may be responsible for the higher leakage exponents. Four factors are considered: leak hydraulics, pipe material behaviour, soil hydraulics and water demand.

The second part of the paper presents the results of an experimental study with different pipe materials. The pipes used were taken from the field in Johannesburg. Also each material fails in a particular manner, the more common failure patterns were encompassed in this study.

The leakage exponents found were in the following ranges:

- Asbestos-cement pipe with longitudinal crack 0.78 – 1.04
- Steel pipe with corrosion cluster 1.90 – 2.30
- Steel and uPVC Pipe with round hole 0.52 – 0.53
- uPVC pipe with longitudinal crack 1.50 – 1.85
- uPVC pipe with circumferential crack 0.40 – 0.52

Introduction

There is renewed international awareness that water distribution systems world-wide are aging and deteriorating, while the demands on these systems, and thus on our natural water resources, are ever increasing. Losses from water distribution systems are reaching alarming levels in many towns and cities throughout the world. Water losses are made up of various components including physical losses (leaks), illegitimate use, unmetered use and under-registration of water meters. Leakage makes up a large part, sometimes more than 70 % of the total water losses (WHO 2001). Water losses have a negative impact on the level of service provided to customers, whilst reducing the income of water suppliers, and increasing the environmental impact of water extractions.

A considerable amount of research has been carried out on water losses and leakage. However, the goal of reducing water losses to acceptable levels remains elusive. It is now recognised that the complexities involved in this problem are much greater than initially thought and that, although much progress has been made in understanding the various factors that affect water losses, much still remains to be done.

One of the major factors influencing leakage is the pressure in a water distribution system. In the past the conventional view has been that leakage from water distribution systems is relatively insensitive to pressure, as described by the orifice equation:

$$q = C_d A \sqrt{2gh} \quad \text{... (1)}$$

Where q is the leakage flow rate, C_d the discharge coefficient, A the orifice area, g acceleration due to gravity and h the pressure head. To apply this equation to leaks in pipes it can be written in more general form as:

$$q = ch^{\alpha} \quad \text{... (2)}$$

Where c is the leakage coefficient and α the leakage exponent. A number of field studies have shown that α can be considerably larger than 0.5 and typically varies between 0.5 and 2.79 with a median of 1.15 (Farley and Trow, 2003). Due to the position of α in equation 2 (as exponent), its value is the overriding factor in determining the flow rate from a particular leak opening. Figure 1 illustrates this point by plotting the fractional change in leakage as a function of the fractional change in pressure for different leakage exponents. If, for instance, the pressure at a leak is halved ($H_1/H_0 = 0.5$), the leakage flow rate will reduce by 29 %, 50 % and 82 % for exponents of 0.5, 1.0 and 2.5 respectively. The substantial differences in the leakage reduction values make it imperative that an accurate leakage exponent value for a network can be estimated.

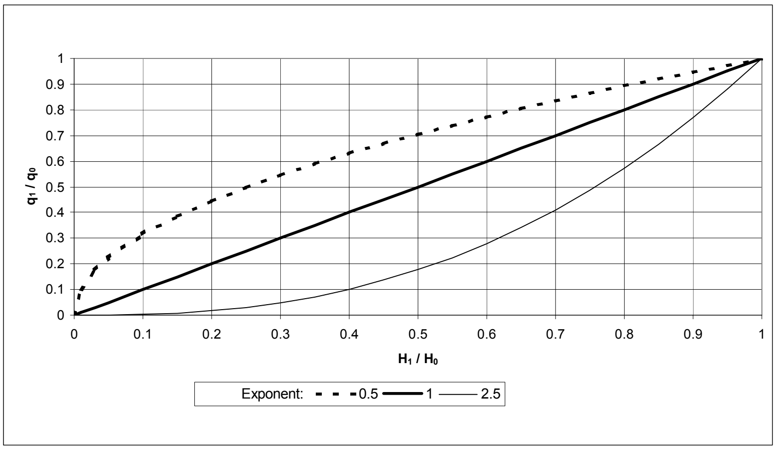

Figure 1 Effect of leakage exponent on the leakage rate

Effect of Pressure on Leakage

Van Zyl and Clayton (2005) discussed the effect of pressure on leakage, and proposed a number of possible mechanisms that are responsible for the observed range of leakage exponents, including leak hydraulics, pipe material behaviour, soil hydraulics and water demand.

Leak Hydraulics

If head losses in the surrounding soil are ignored, a leak opening in a pipe is hydraulically equivalent to an orifice on the side of a tank. While the leakage exponent of an orifice of fixed diameter is universally accepted as 0.5, the discharge coefficient is often not constant, but is expressed as a function of the Reynolds number (Re). It is thus conceivable that a certain type of leak can be modelled using a fixed discharge coefficient, but with an exponent higher or lower than 0.5.

Another important hydraulic future comes into play in laminar flow, which is characterised by a linear relationship between head loss and flow rate. Flow through orifices is laminar at Re below about 10 and turbulent above about 4000. Intermediate values represent the transitional zone where the leakage exponent can vary between 1 (at the laminar/transitional boundary) and 0.5 (at the transitional/turbulent boundary). The maximum laminar and maximum transitional flow rates were calculated for different types of leak openings and are shown in figure 2. Cracks are represented by a rectangular opening with a large length to width (l/b) ratio.

The figure shows that cracks can have much higher laminar or transitional flow rates than round or square holes. This is due to the role of their much larger wetted perimeters. While full laminar flow is unlikely to play a significant role in leakage due to the small flow rates, transitional flow can be an important cause of background leakage, and thus contribute to a leakage exponent above 0.5 (although not above 1.0).

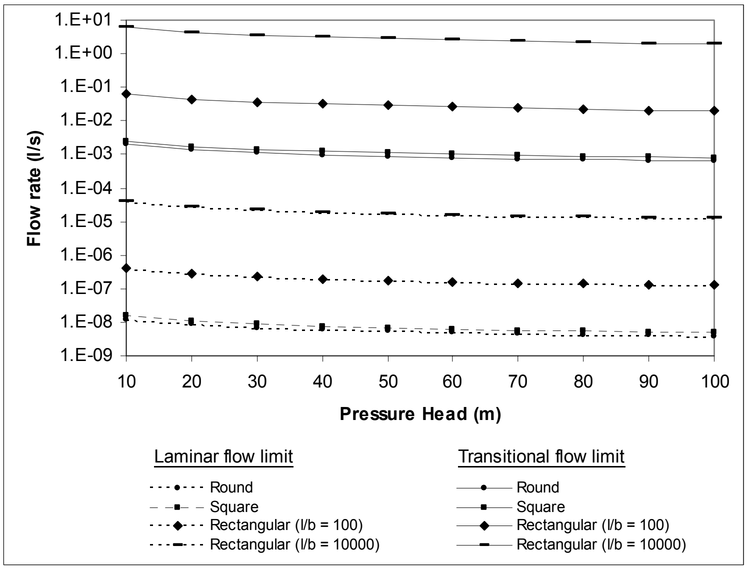

Figure 2 Maximum laminar and transitional flow rates for different types of leak openings (from Van Zyl and Clayton 2005)

Pipe Material Behaviour

Pipe material plays an important role in the leakage behaviour of pipes. Due to the material properties, pipes of different materials will fail in certain characteristic ways. Water pressure in a pipe is taken up by stresses in the pipe wall, and thus may play an important role in the failure and leakage behaviour of pipes made of lower strength materials. The following effects can be linked to an increase in the internal pressure in a pipe:

Small cracks or fractures that do not leak at low pressure and high temperature can open up to create new leaks at the higher pressure.

The area of an existing leak opening in a pipe can increase due to the increased stresses in the pipe wall.

An increase in the frequency of pipe bursts.

Theoretical work carried out at the University of Johannesburg's Water Research Group developed the following basic model for the flow rate through a round hole in an elastic pipe:

$$Q = C_d \frac{\pi d_0^2}{4} \sqrt{2g} \left(H^{\frac{1}{2}} + \frac{2c\rho g D}{3tE} H^{\frac{3}{2}} + \frac{c^2 \rho^2 g^2 D^2}{9t^2 E^2} H^{\frac{5}{2}} \right) \quad \text{... (3)}$$

Where d_o is the original hole diameter, D is the pipe diameter, t the pipe wall thickness, E the elasticity modulus and c a constant. The relationship shows that the processes involved in the expanding leak opening are more complex than the simple power relationship normally used to describe leakage. The equation contains the sum of three terms with leakage exponents of 0.5, 1.5 and 2.5 respectively, which seems to tie in well with field and experimental observations.

The results of an experimental study on the leakage behavior of failed pipes are presented later in the paper. It is believed that pipe material behaviour is the main cause of observed leakage exponents above the theoretical orifice value of 0.5.

Soil Hydraulics

Van Zyl and Clayton (2005) concluded that the interaction between a leaking pipe and its surrounding soil is complex. The relationship between head loss and flow is unlikely to be linear, as a result of interaction of soil particles with the orifice, turbulent flow in the soil, the changing geometry of the unconfined flow regime, hydraulic fracturing and piping. Theoretical considerations suggest that small continuous leaks from pipes will drain away without trace into underlying granular soil. This cannot be expected to occur in lower permeability clays and silts, where hydraulic fracture is more likely, with leaks rapidly becoming visible as wet patches and bursts at the ground surface.

Water Demand

Water demand cannot be classified as leakage, but it is often impossible to separate legitimate water consumption from leakage measurements in the field. It is thus important to understand the behaviour of water demand as a function of pressure. In a study of water consumption patterns at a student village on the campus of the University of Johannesburg, Bartlett (2004) found the indoor demand elasticity for pressure to be approximately 0.2. Outdoor water consumption such as garden irrigation is typically time-based rather than volume-based, meaning that a higher exponent can be expected for outdoor use, although this exponent is unlikely to exceed 0.5.

In large systems it becomes likely that even minimum measured night flows will include some legitimate consumption. Since the combined “leakage exponent” for outdoor and indoor consumption is likely to be less than 0.5, it may be concluded that measured leakage exponents in systems with demand are likely to underestimate the true leakage exponent of the system, provided that the level of demand in the measured night flows do not differ significantly.

Methodology

The experimental setup (see figure 3) consisted of two removable end sections fitted to a failed pipe section using Viking Johnston couplings. One end section was connected to the municipal water supply network through a combination turbine flow meter. The downstream end was fitted with a calibrated pressure transducer. The system was held together with a number of threaded steel rods and end supports. Readings from the flow meter and pressure transducer were collected using a data logger. Pressure was recorded at half second intervals and flow rate from a pulse from the flow meter for every one litre of flow.

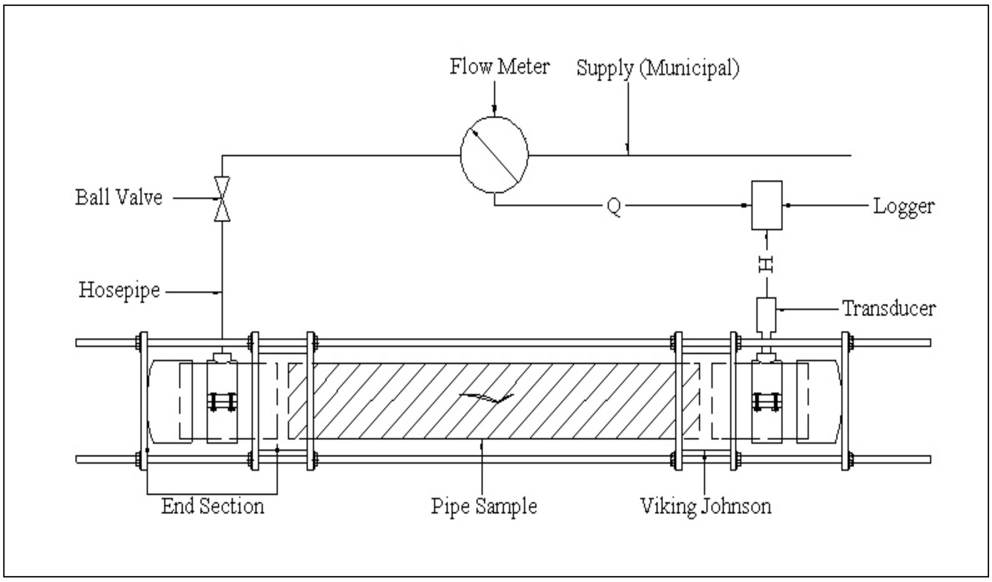

Figure 3 Experimental setup

The flow and pressure in the system were controlled by a lever ball valve on the upstream supply pipe. The leak discharged into the atmosphere and no flow existed in the system apart from the leak flow rate. A small flow was first induced to remove all trapped air. The setup was then placed horizontally with the pressure transducer and leak at the same level. Flow and pressure were increased and then decreased in steps lasting at least 30 seconds each. This procedure was repeated three times before ending the experiment and analysing the data.

It was found that both the pressure and flow measurements included short term fluctuations. This is due to the transients that exist in the municipal water distribution system used to supply the flow and pressure for the experiments. Under low flow and pressure conditions, the amplitude of the fluctuations is smaller due to the dampening effect of the throttling valve. The effect of the short term pressure fluctuations on the behaviour of the leaks is not known, but since such fluctuations will occur naturally in most water distribution system, no attempt was made in these experiments to remove the fluctuations.

Experimental data points were obtained by identifying relatively stable sections of the flow and pressure graphs and then taking the average values over each of the ranges. These average values were then plotted and analysed to determine the leak exponent for each leak opening. A typical experimental result is shown in figure 4 for tests on asbestos cement pipes taken from the field.

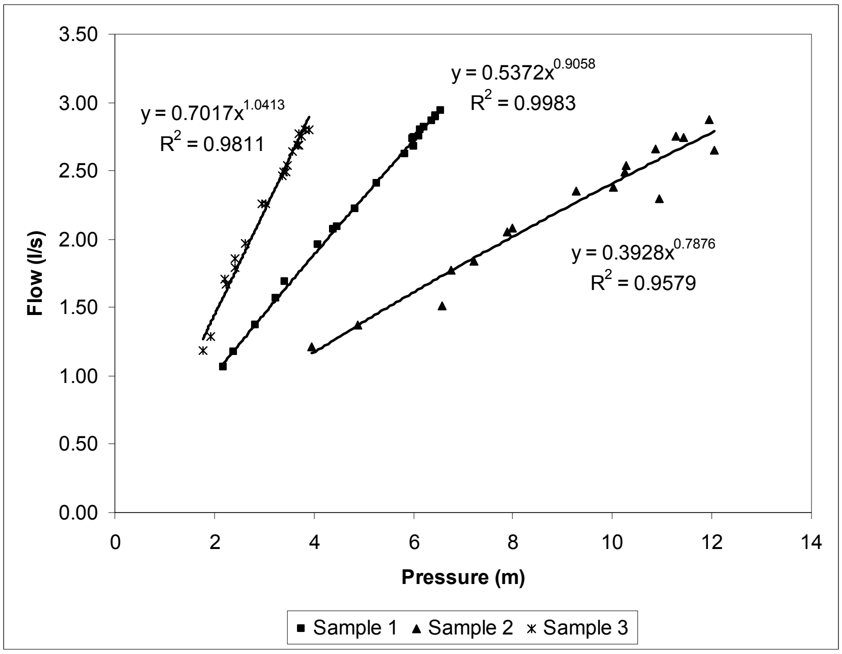

Figure 4 Typical results: behaviour of leak openings in asbestos cement pipe samples

Results and Discussion

Asbestos Cement pipes

Three failed asbestos cement pipe sections taken from the field in Johannesburg were tested. The sections are shown in figure 5. All three samples have outer diameters of 100 mm and wall thicknesses of 12 mm. Each failure consisted of a longitudinal crack starting at one end of the pipe section and ending in a bell shaped crack.

Figure 5 Failed asbestos cement pipe sections

The Reynolds numbers were in excess of 5000 for all tested points, indicating fully developed turbulent flow. The exponents determined for the three pipe sections were 0.91, 0.79 and 1.04 respectively.

The leakage exponents found are significantly higher than the theoretical orifice exponent of 0.5. No clear relationship between crack length and exponent could be determined from the results. Samples 1 and 3 had the highest exponents, both near unity.

Sample 2 displayed the lowest leakage exponent even though the length of its crack was not the shortest. This may be due to the fact that its crack follows a slightly diagonal path, unlike samples 1 and 3 where the cracks are parallel to the centre line of the pipes. It is likely that the higher than expected exponents are caused by the cracks opening with increasing pressure in the pipes.

Steel pipes

Three failed mild steel pipe sections taken from the field in Johannesburg were tested. Another test sample was created by drilling a round hole in an otherwise good quality mild steel pipe. The sections (excluding the drilled hole sample) are shown in figure 6.

Figure 6 Failed steel pipe sections

The Reynolds numbers were high enough to ensure turbulent flow for all data points. The exponents determined for the three samples with corrosion holes (4, 5, 6 and 7) are 0.67, 1.96, 2.30 and 0.518 respectively.

The highest exponents were found in pipes with extensive corrosion damage to the pipe wall. In addition to the holes in the pipe wall, the surrounding material had been significantly reduced through corrosion. This reduction in the supporting material surrounding the leak openings means that higher stresses and strains will develop and that the leak area will thus increase more. This effect will be amplified as pressures increase and is believed to be the main reason for the high exponents found.

The very high exponents found indicate that the maximum exponents in excess of 2.5 reported in field tests (Farley and Trow 2003) are not unrealistic. Such high exponents will play an overriding role in the leakage behaviour of a system, and thus have important implications for pressure management, material selection and maintenance of existing systems.

uPVC pipes

No failed uPVC pipe sections could be obtained for testing in this study. However, a number of tests were performed with artificially induced leak openings in the form of a hole, and longitudinal and circumferential cracks. A new 110 mm class 6 uPVC pipe with a wall thickness of 3 mm was used for all tests.

Sample 8 consists of a 12 mm diameter round hole drilled into a uPVC pipe section. All Reynolds numbers were above 100 000 and the flow is thus turbulent for all data points. The exponent found for this sample is 0.524, slightly higher than that of the 12 mm round hole in the steel pipe. The slightly higher leakage exponent than for steel might be explained by the combination of a lower modulus of elasticity and wall thickness of the uPVC pipe resulting in greater expansion of the leak area with increasing pressure. However, both exponents are close to the theoretical leakage exponent of 0.5, indicating that the increase in leak area is relatively small for both cases.

Three circumferential cracks with a width of 1 mm and lengths of 90, 170 and 270 mm were created in the uPVC pipe sections for samples 9, 10 and 11. The Reynolds number is in excess of 10 000 for all tested points, indicating fully developed turbulent flow. The exponents determined for the three samples were 0.41, 0.50 and 0.53 respectively. The exponents do not differ much from the theoretical orifice exponent of 0.5, but a clear trend of increasing leakage exponent with increasing crack length is evident. This is probably due to the longitudinal forces on the crack walls being higher for longer cracks (due to their larger lengths) causing the longer cracks to increase more in area than the shorter cracks.

An interesting observation is the exponent of 0.41 for the shortest crack. An exponent below 0.5 indicates that the leak area is decreasing with increasing pressure. This can be explained if it is taken into consideration that the theoretical circumferential stress in a pipe is double the theoretical longitudinal stress (for example, see Benham et al., 1996). In the experimental setup used, the longitudinal stresses are mainly taken up by the frame and thus will be considerably lower than the theoretical value. The initial value of the longitudinal stress should be zero, but tightening the support structure too much can even induce negative (compression) longitudinal stresses in the pipe. The circumferential stresses in the experimental setup were thus substantially higher than the longitudinal stresses. It is thought that the circumferential stresses caused the cracks to elongate, and at the same time reduce in area, thus causing the leakage exponent to be lower than 0.5.

Pipes in the ground are surrounded by soil and often supplied with constructed end supports causing the soil and supports to take up much of the stresses in the pipe material. The longitudinal stresses in the pipe material will be determined by factors including the network layout, bedding soil properties, soil movements, and thermal expansion and contraction of the pipe material due to changes in water temperature. It is thus difficult to predict what the longitudinal stresses in pipes in the field, although it can be safely assumed that these stresses will generally be significantly lower than the circumferential stresses.

Three longitudinal cracks with a width of 1 mm and lengths of 86, 100 and 150 mm were created in the pipe sections for samples 12, 13 and 14. The Reynolds number is in excess of 10 000 for all tested points, indicating fully developed turbulent flow. The overall exponents determined for the three samples were 1.51, 1.46 and 1.85 respectively. The tests were characterised by significantly more scatter in the data than for circumferential cracks. The exponents are substantially higher than the theoretical orifice exponent of 0.5. Although the exponent for the 86 mm crack is slightly higher than the 100 mm crack, there seem to be a trend of increasing exponent with increasing crack length. The reason for these exponents is probably that the cracks are pulled open by the circumferential stresses that increase with increasing pressure in the pipe.

Discussion

The leakage exponents found are summarised in table 1 and figure 7. The table shows that leakage type is a better indicator of leakage exponent than pipe material. For round holes in otherwise good quality pipes, the leakage exponents are close to the theoretical orifice exponent of 0.5, and are similar for uPVC and steel pipes.

Table 1 Summary of leakage exponents found in this study

Failure type	Leakage exponent for pipe material		
	uPVC	Asbestos cement	Mild steel
Round hole	0.524	-	0.518
Longitudinal crack	1.38 – 1.85	0.79 – 1.04	-
Circumferential crack	0.41 – 0.53	-	-
Corrosion cluster	-	-	0.67 – 2.30

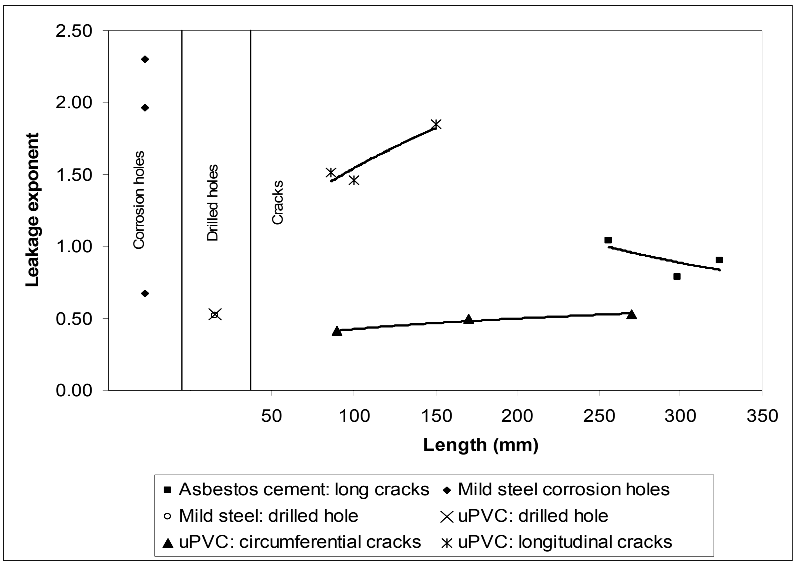

Figure 7 Summary of leak exponents found in this study

Longitudinal cracks presented leakage exponents substantially larger than the theoretical orifice exponent of 0.5. The uPVC exponents are larger than those of asbestos cement, probably due to lower values in both uPVC's modulus of elasticity and wall thicknesses. In uPVC pipes, the exponents found for circumferential cracks proved to be much lower than those of longitudinal cracks, being near and, significantly, also below the theoretical orifice value of 0.5. It is suggested that the main factors responsible for this difference are possibly a larger rigidity of the cross-sectional section of the pipe compared to the longitudinal section, and large differences normal stresses in the pipes in the longitudinal and circumferential directions.

The highest exponents were found in the corrosion clusters in steel pipes. This is contrary to the perception (Farley and Trow 2003) that plastic pipes will have higher leakage exponents due to their lower modulus of elasticity.

Conclusions

This paper reports on an experimental study to determine the leakage exponents for failed water pipes taken from the field, and for pipes with artificially induced leaks. The study included round holes, and longitudinal and circumferential cracks in uPVC, steel and asbestos cement pipes. All flows were turbulent and leaks were exposed to the atmosphere. The resulting leakage exponents varied between 0.42 and 2.30 as shown in table 1. The main findings of the study were:

- The exponents found confirm that the leakage exponents found in field studies are not unrealistic.

- The highest leakage exponents occurred in corroded steel pipes, probably due to corrosion reducing the support material around the hole. This is contrary to the perception (Farley and Trow 2003) that plastic pipes will have higher leakage exponents due to their lower modulus of elasticity.
- Round holes had leakage exponents close to the theoretical value of 0.5 and only a small difference was observed between steel and uPVC pipes.
- Besides corrosion holes, the largest exponents were found in longitudinal cracks. This is due to the fact that circumferential stresses in pipes are typically higher than longitudinal stresses.
- The leakage exponent for circumferential cracks in uPVC pipes could be less than 0.5, indicating that the leak opening is contracting with increasing pressure. This is explained by the fact that the experimental setup did not allow substantial longitudinal stresses to develop in the pipe. It is thought that the circumferential stresses caused the cracks to elongate, and at the same time reduce in area.

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