An Experimental Investigation into the Pressure - Leakage Relationship of Some Failed Water Pipes

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Short title: Experimental Investigation into Pressure and Leakage

ABSTRACT

This paper reports on an experimental study that was conducted to measure the leakage exponents of different types of leak openings (holes, corrosion holes, and longitudinal and circumferential cracks) and pipe materials (asbestos cement, mild steel and uPVC). A number of failed pipes taken from the Johannesburg water distribution systems were tested, as well as a number of pipes with artificially induced leaks. The results of the study confirmed that leakage exponents can be significantly higher than the theoretical value of 0.5. While leakage exponents for round holes were close to 0.5, the values for corrosion holes varied between 0.67 and 2.30, for longitudinal cracks between 0.79 and 1.85, and for circumferential cracks between 0.41 and 0.52. Conclusions include that the highest leakage exponents were found in corroded steel pipes and that under certain circumstances, leakage exponents can be less than 0.5.

Keywords: Leakage, pressure, pipe, failures, distribution, water

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, much of it lead and coordinated by the IWA Water Loss Task Force (Thornton 2003). 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 (Thornton and Lambert 2005, Charalambous 2005). 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:

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

Where q 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:

$$q = c\,h^{N1} \qquad \text{... (2)}$$

Where c is the leakage coefficient and $N1$ the leakage exponent. A number of field studies have shown that $N1$ 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 $N1$ 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.

Van Zyl and Clayton (2005) 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.

This paper reports on an experimental study that was conducted to measure the leakage exponents of different types of leak openings and pipe materials. A number of failed pipes taken from the Johannesburg water distribution systems were studied, as well as a number of pipes with artificially induced leaks. The leakage exponents obtained for the different leak types and pipe materials are compared and an attempt is made to explain the values found.

METHODOLOGY

The experimental setup (see figure 2) consisted of two removable end sections fitted to a failed pipe section using flexible 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 on a data logger. Pressure was recorded at half second intervals and flow rate flow meter generating a pulse for every one litre of flow.

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 and the setup tilted towards the opened valve on the downstream end section to remove all trapped air. The setup was then placed horizontally with the pressure transducer and leak on 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 in succession before downloading and analysing the data.

A typical raw data set is showed in figure 3. The X scale of the figure is compressed inducing some distortion in the graphs. It is clear from the figure that both the pressure and flow 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 to remove them.

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 leakage exponent for each leak opening.

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 4. 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. The lengths of the exposed cracks in the experimental setup, excluding the bell shaped parts, were 324, 298 and 256 mm respectively for samples 1, 2 and 3.

The results of the experiments are shown in figure 5. The Reynolds number is 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 coefficients of determination for the power curves fitted to the data were 0.998, 0.958 and 0.981 respectively, indicating good data fits.

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. Sample 4 has an outer diameter of 115 mm and a wall thickness of 3 mm. It has two corrosion holes, one with diameter of approximately 20 mm and another with a diameter of approximately 4 mm. The wall thickness of the pipe material around the 20 mm hole is approximately 0.04 mm.

Sample 5 has an outer diameter of 90 mm and a wall thickness of 4 mm. Three corrosion holes are evident: the leftmost hole is roughly circular and has an average diameter of 20 mm. The central elongated hole has a length of 43 mm and a maximum width of 11 mm.

The rightmost hole is roughly triangular with sides approximately 30 mm in length. It was observed that the wall thickness of the material surrounding the holes is very thin.

Sample 6 has an outer diameter of 85 mm and a wall thickness of 3 mm. One side of the pipe displays a corrosion cluster consisting of more than 25 holes with diameters ranging from 2 mm to 10 mm. The wall thickness between and surrounding the holes is very thin.

Sample 7 has an outer diameter of 110 mm and a wall thickness of 4 mm. This pipe section was taken from the field, but is relatively new and while rust is evident on the pipe surface, the wall thickness is maintained throughout. A hole with a diameter of 12 mm was drilled into the pipe wall.

The results of the experiments are shown in figure 7. The Reynolds numbers were high enough to ensure turbulent flow for all data points. The leakage rates in the tests for samples 5 and 6 were very high and the experimental pressures in the samples hardly exceeded 2 m. While it would be beneficial to test these samples under higher pressures, the mechanisms responsible for the behaviour is not expected to change significantly. The exponents determined for the three samples with corrosion holes (4, 5, and 6) are 0.67, 1.96 and 2.30 respectively. The coefficients of determination for the power curves fitted to the data were 0.978, 0.798 and 0.927 respectively, indicating good data fits for samples 4 and 6, but less good due to a significant amount of scatter in the lower pressure data for sample 5.

The leakage exponent found for sample 7 with a drilled 12 mm hole is 0.518. The power trend line fitted the 14 data points with a very good coefficient of determination of 0.99995, indicating a high level of both accuracy and repeatability in this experiment.

The high 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. This argument is supported by the relatively low exponents found for sample 7 with no significant corrosion damage, and sample 4 with fewer holes and significantly less corrosion than samples 5 and 6.

Van Zyl and Clayton (2005) reported on a theoretically derived equation for the flow through a round hole, taking pipe stresses and strain into account:

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

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. Plotting this equation for typical pipe values, it is clear that the last two terms do not play an important role under normal pressure conditions, and that the combined leakage exponent remains close to 0.5. This is also confirmed by experimental results of sample 7. However, if the wall thickness is reduced through corrosion or some other mechanism, the second and third terms in the equation are increased (due to t occurring below the line). This is another indication that the higher exponents are caused by an increase in the hole area with increasing diameter.

The 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. All Reynolds numbers were above 100 000 and the flow is thus turbulent for all data points.

Round hole

Sample 8 consists of a 12 mm diameter round hole drilled into a uPVC pipe section. The result of this test is shown in figure 8.

The exponent found for this sample is 0.524, slightly higher than that of the 12 mm round hole in the steel pipe. The power trend line has a very good coefficient of determination of 0.99986, indicating a high level of both accuracy and repeatability in this experiment. 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.

Circumferential cracks

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 (figure 8). The results of the experiments are shown in figure 9. The exponents determined for the three samples were 0.41, 0.50 and 0.53 respectively. The coefficients of determination for the power curves fitted to the data were 0.989, 0.995 and 0.998 respectively, indicating good data fits.

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 greater 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.

Longitudinal cracks

Three longitudinal cracks with a width of 1 mm and lengths of 50, 100 and 150 mm were created in the pipe sections for samples 12, 13 and 14 (figure 10). Immediately after starting the tests, the 50 mm crack opened up further to a total length of 86 mm. The results of the experiments are shown in figure 11. 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, leading to worse coefficients of determination of 0.954, 0.974 and 0.875 respectively.

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 seems to be a trend of increasing exponent with increasing crack length. The likely reason for these exponents is 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. 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.

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 likely due to large differences in 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 commonly held perception 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 are that:

- 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 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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TABLES

Table 1 - Summary of leakage exponents found

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

FIGURES

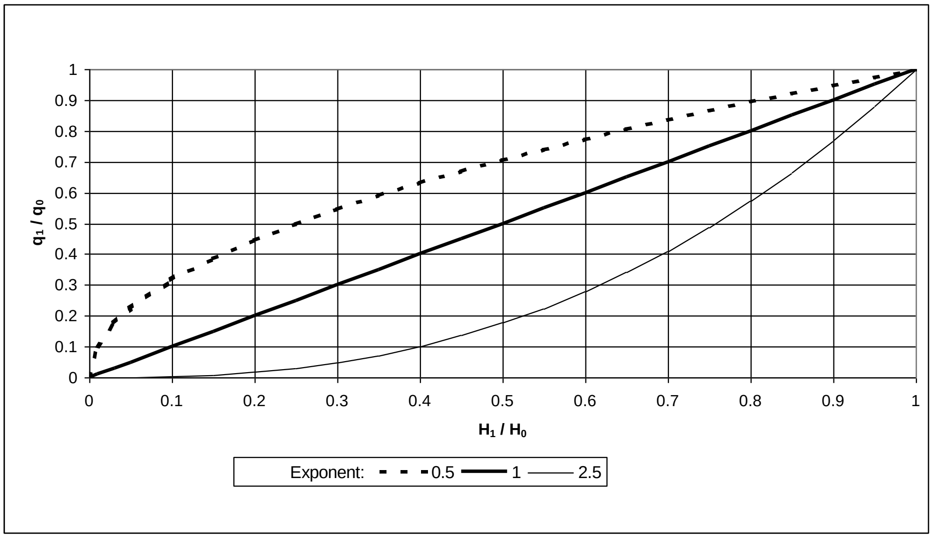

Figure 1 - Effect of leakage exponent on the leakage rate

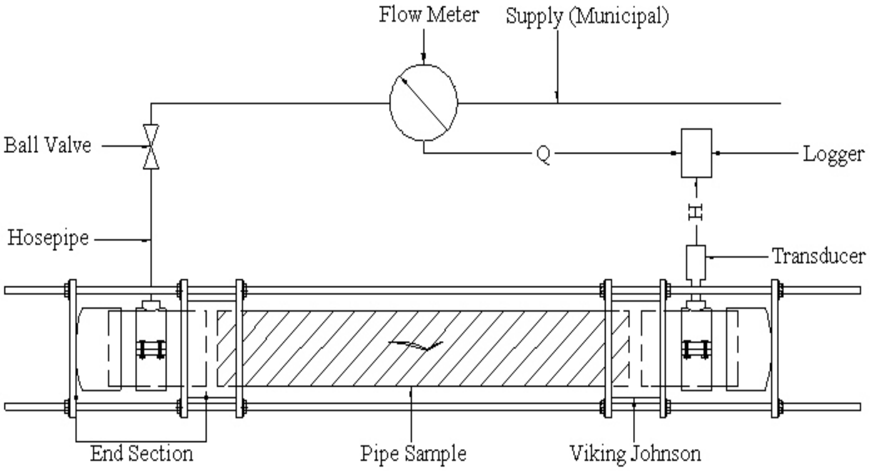

Figure 2 - Experimental setup

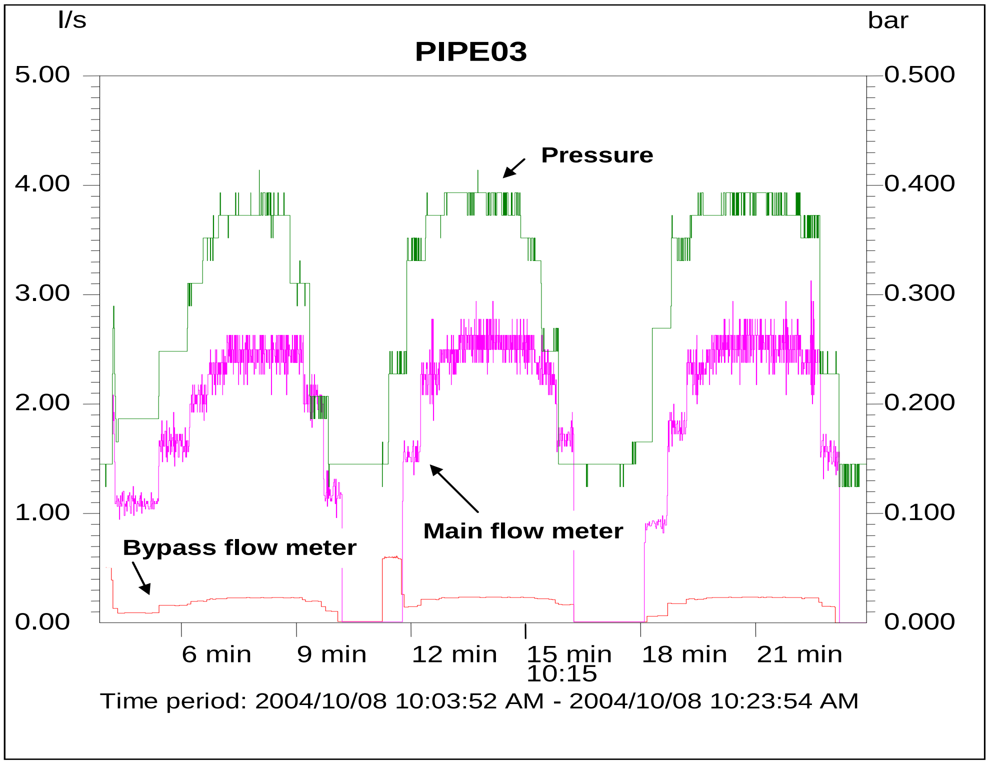

Figure 3 - Typical measured data

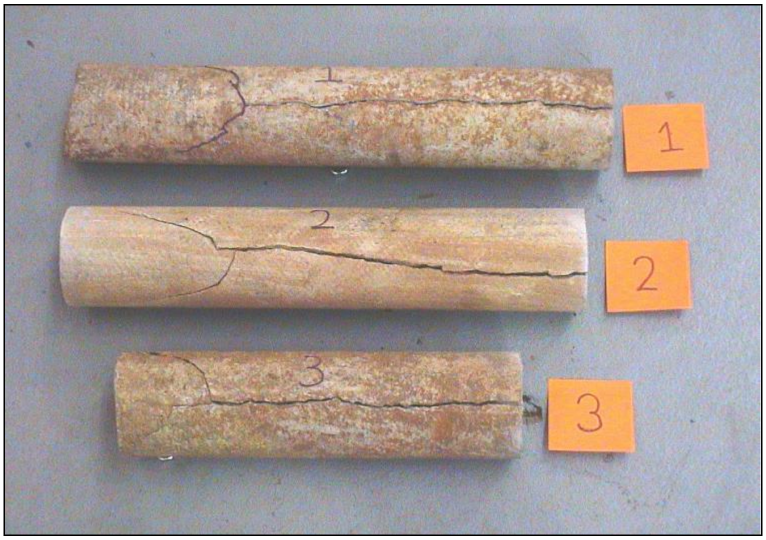

Figure 4 - Failed asbestos cement pipe sections

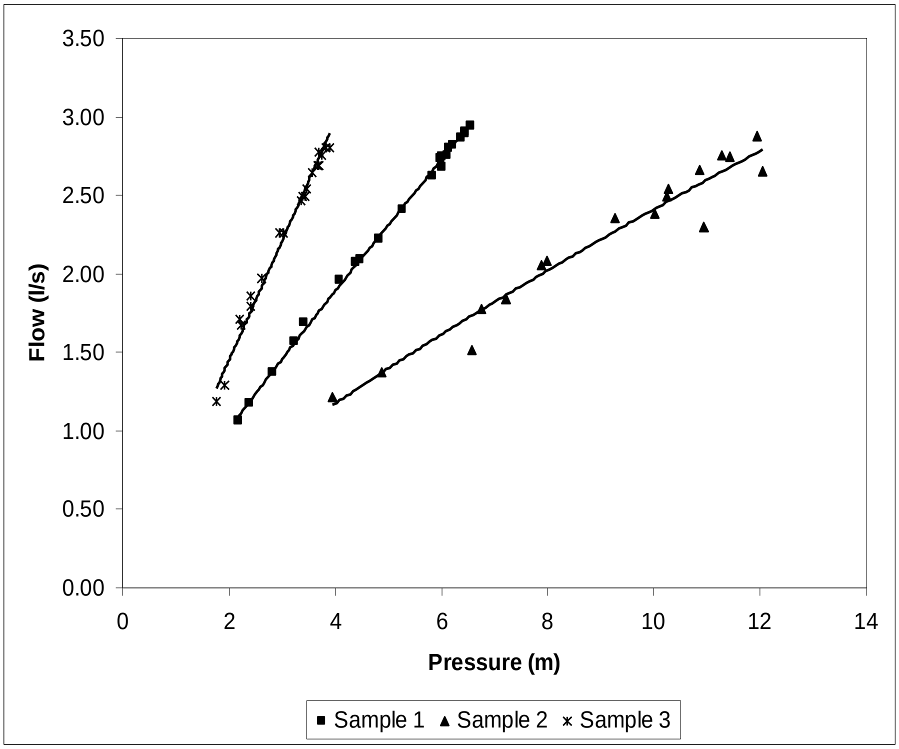

Figure 5 - Behaviour of leak openings in asbestos cement pipe samples

Figure 6 - Failed steel pipe sections

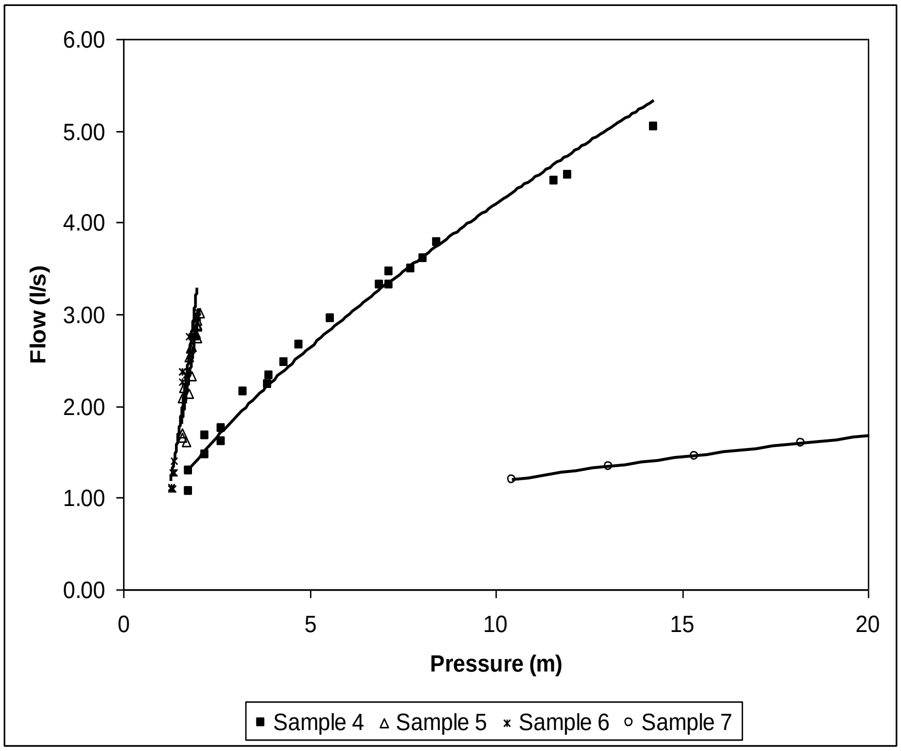

Figure 7 - Behaviour of leak openings in mild steel pipe samples. Results for sample 7 are only shown below 20 m, although test pressures up to 67 m were measured.

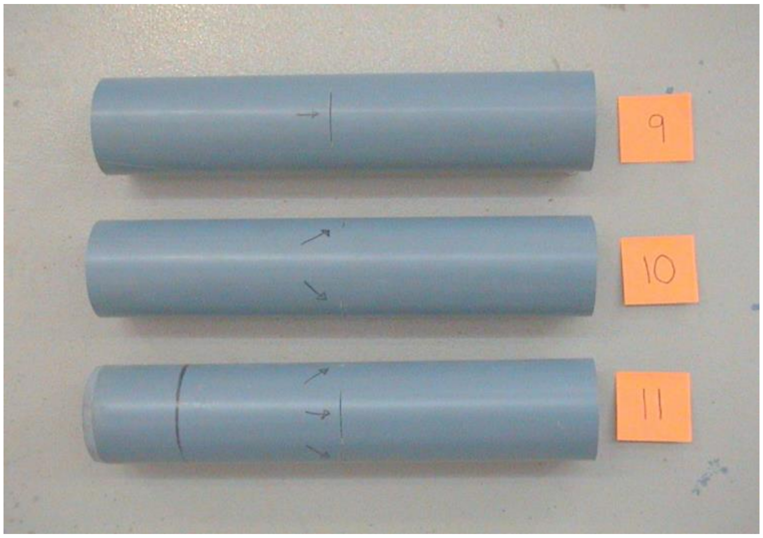

Figure 8 – Circumferential cracks in uPVC

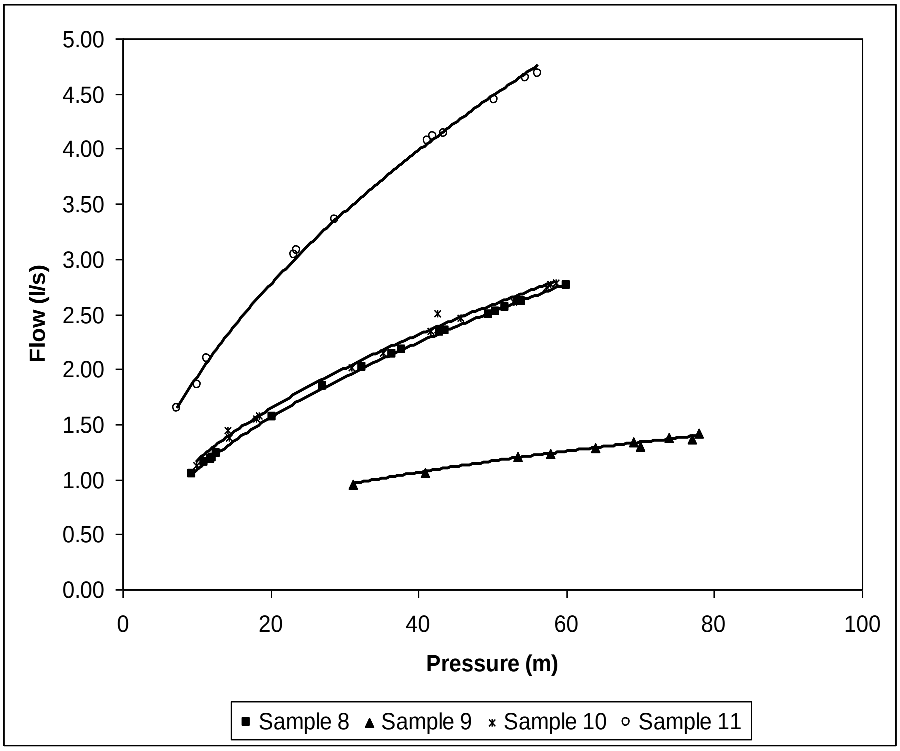

Figure 9 - Behaviour of circumferential cracks and a round hole in uPVC pipe samples.

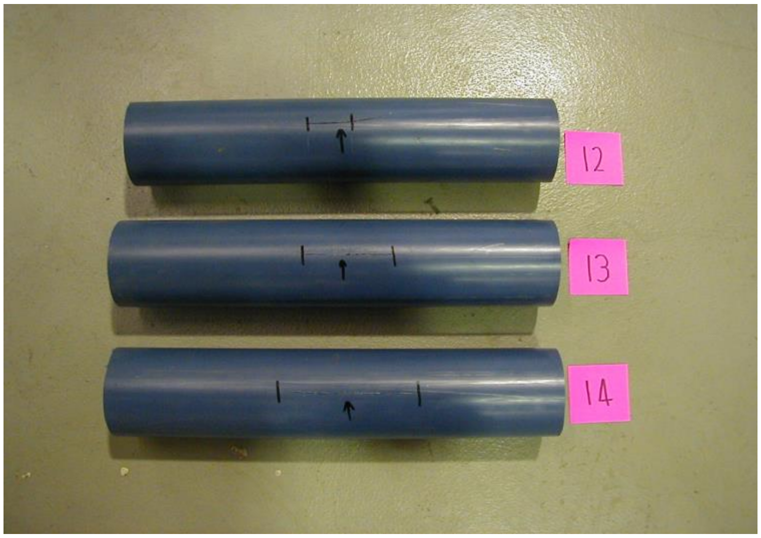

Figure 10 – Longitudinal cracks in uPVC

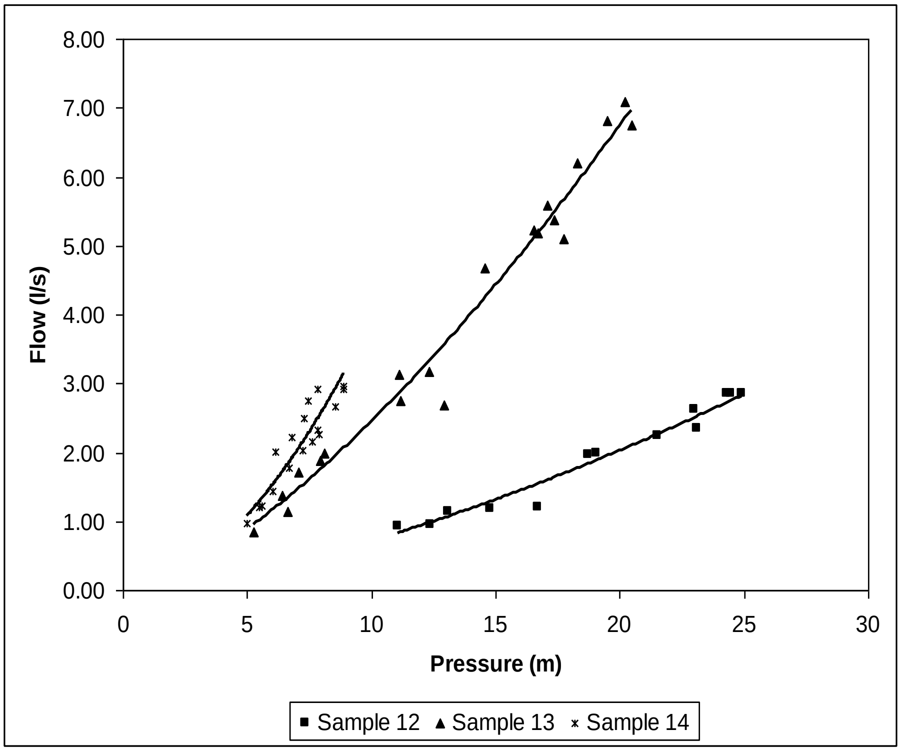

Figure 11 - Behaviour of longitudinal cracks in uPVC pipe samples