PREDICTING THE RESIDUAL LIFE OF PVC SEWER PIPES.

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ABSTRACT

Ipswich Water commenced reviewing the service lives of different pipe materials in its gravity sewer system. Unlike other pipe materials, PVC sewers did not have failure histories, or deterioration revealed in CCTV inspections, even after 25 years of service. Therefore establishing a realistic predicted life was not possible using statistical analysis of historical field failure data. The approach taken was to exhume a number of elastomeric seal jointed PVC sewer pipes that had been in service for periods of up to 25 years. The samples were tested for selected mechanical properties and joint performance characteristics which might be considered age dependant. The results indicated there had been no deterioration in the material and the joints continued to meet current performance specifications. Two methods of quantifying the condition of PVC sewer pipelines and predicting the residual life are suggested. Based on this analysis, the pipelines examined have not exhibited any significant deterioration and should provide many more years of service.

INTRODUCTION

A number of overseas studies have been made into the effects of ageing of PVC sewer pipes.
Moser et al (1) examined the long-term creep characteristics and physical properties of PVC pipes buried over 14 years and found there was no change in stiffness or resistance to flattening. Bauer (2) examined 10 inch PVC sewer pipes that had been in service for 15 years. The pipes exhibited no evidence of loss of wall thickness due to abrasion and no deterioration of mechanical properties. Janson (3, 4) reported on the performance of PVC sewer pipe aged for over 9 years under controlled conditions and reported there was no reduction in the ability of the pipes to resist loads. Alferink et al (5) examined a number of exhumed sewer pipes. They found no evidence of reduction in yield strength, stiffness or wall thickness. Staining of PVC sewer pipes in the immersed part of the internal wall and the outside wall in acid soils has been reported (6) and shown to not adversely influence the mechanical properties of the pipe. The affect of sulphuric acid on PVC sewer pipes was studied by Hawkins and Mass (7). They concluded there was no basis for concerns about sewer-gas acids attacking the calcium carbonate filler.

In the present study PVC pipes, made to the Australian Standard applicable at the time of manufacture and subjected to Australian installation and service conditions, were exhumed and subjected to a range of mechanical tests on the material and joints. In addition, an assessment was made of any possible loss of wall thickness due to abrasion.

RESIDUAL LIFE OF THE PIPES

Sagrov (8) proposed a method of assessment of the durability of concrete sewer pipes. The method entailed measuring those characteristics of the pipe that are considered to influence its life. Each characteristic was assigned a reference value R_I representing an acceptable value and a weighting factor W_I dependant on the significance of the quality being considered. The actual test result was identified as M_i. The quality number Q was determined according to equation (1).

$$Q = \sum_{i=1}^{n} W_i \times \frac{M_i}{R_i} \qquad (1)$$

Where n = number of test methods

Sagrov nominated several quality number intervals including 0.8 – 1.0 (good), 0.6 – 0.8 (acceptable) and 0.4 – 0.6 (non-suitable). In this work, 0.8 – 1.0 has been designated as "acceptable". Pipes are assumed to have a quality number of 1 at the time of installation. In the case of PVC sewer pipes the characteristics that will determine the residual life of the pipe are expected to be joint integrity, loss of wall thickness or deterioration in strength or stiffness of the pipe matrix. In this work it is assumed the ovality of the buried pipe is largely determined by the installation conditions and can be monitored in situ. Whilst physical ageing of PVC would be expected to result in an increase in some of the strength characteristics it is proposed that the ratio $\frac{M_i}{R_i}$ be restricted to a maximum of one. This is intended to prevent the anomalous situation where a pipe that has been in service for a short time apparently has a longer residual life than when first installed. It must also be recognised that a catastrophic result in one characteristic should not be overridden by good results in others.

An alternative, mathematical technique using linear multivariate regression analysis has also been applied to the data. Again a lower acceptable limit of 0.8 has been arbitrarily applied to the quality number.

PIPE DETAILS AND OPERATING CONDITIONS

A total of seven pipes, as detailed in Table 1 were exhumed. Six of the pipes were received from Ipswich Water. The seventh was exhumed by Sydney Water at Winmalee in the Lower Blue Mountains. All pipes were class SH which is equivalent to an SDR of 38.

TESTING

The pipes were subjected to a series of tests to determine the condition of the pipe material, assess the integrity of the joints and ascertain whether there had been any loss of wall thickness due to abrasion.

The pipes samples were cut to length and mounted in a pressure test rig with restrained end enclosures. Each assembly was filled with water and subjected to an internal pressure of 80 + 5, -0 kPa for 60 +5, -0 minutes at 20°C. The joints were examined for any evidence of leakage. At the completion of the pressure test the assemblies were drained and subjected to an internal vacuum corresponding to a gauge pressure of –80 –5, +0 kPa for 60 +5, -0 minutes, also at 20°C. Again the joints were examined for any evidence of leakage.

TABLE 1. Details of Exhumed Pipes.

Parameter	Sample Number						
	00/1	00/2	00/3	00/4	00/5	00/6	00/7
Source	Ipswich						Winmalee
Nominal Diameter	150				225		150
Year Made	1975		1984		1989		1980 Est.
Burial Depth mm	1500	3500	1800	800	2250	800	2000
Depth of Flow %	15%	15%	15%	10%	20%	35%	Very low
Temp. of Flow ^{0}C	22.4	22.4	25.8	25.8	25.1	25.2	-
Sample Location	Private Property				Park		
Condition sample	Good			Damaged	Good		
Infiltration	None						
Evidence of Gas	None						-
Bedding	Sand				Gravel		-
Back Fill	Excavated Material				Lean Mix	Excavated Material	
Built-over?	No						
Type of surrounding Soil	Black soil		Clay and Crushed Rock		Black Soil		Silty gravel
Trees nearby?	One		No				Yes
Distance to trees m	>3.0		N/A				2

The profile of the interface pressure between the spigot and elastomeric seal was measured for each joint in accordance with the revised Australian/New Zealand Standard, AS/NZS1462:13. The flattening test was performed on each pipe sample by compressing a hoop of the pipe between parallel plates to 40% of its original diameter.

The pipe stiffness was measured at a deflection equal to 5% of the internal diameter in accordance with AS/NZS 1462:22. The flexural modulus was then calculated from the relationship between the pipe stiffness, diameter and wall thickness according to equation (2).

$$PS = \frac{EI}{D^3} \qquad (2)$$

Where *PS* is the pipe stiffness, *E* the flexural modulus, *I* the second moment of area of the pipe wall section and *D* the mean pipe diameter.

The resistance to impact was measured using an instrumented machine with an indentor of 12.5mm diameter travelling at a velocity of approximately 1.5m/s. The samples were tested by impacting half sections of pipe centred over a hole in the plate upon which the section was supported. The results were reported as either brittle or no fracture. The peak load, and in the case of brittle fracture, also the load at break were recorded. The yield strength, yield strain, ultimate tensile strength and ultimate elongation were measured to ASTM D638 with Type 1 specimens and a crosshead speed of 5mm/min. In each case the reported result is the average of at least 7 dumbbells.

The gelation level and processing temperature were determined by differential scanning calorimetry (DSC). Whilst these characteristics are not specified in any of the relevant product standards, the results provide a means of comparing processing conditions between the exhumed pipes and contemporary product.

The wall thickness of each pipe was measured by micrometer at 45° intervals around the circumference, starting at the crown. The crown was identified by the markings made at the time of exhumation and was confirmed by the location of the black, sulphide staining at the invert of the pipe (Fig. 1).

RESULTS AND DISCUSSION

With the exception of sample 00/4, all the joints passed both the infiltration and exfiltration tests. Sample 00/4 leaked in both tests because of damage to the spigot that apparently caused by an excavator. There was a long score mark along the top of the spigot which ended at the socket which was also damaged. The stress that had been applied to the top of the pipe was sufficient to permanently distort the spigot (Figs. 2 – 3). There was also damage evident on the socket of 00/6 (Fig. 4) that looked like a crowbar or tooth from an excavator had caught the lip of the socket. This did not cause failure in either the pressure or vacuum test. It was observed that many of the pipes exhibited a staining pattern that had the appearance of tree roots in contact with the pipe (Fig.5). The results show that except in the case of the damaged spigot, the joints have maintained their integrity for up to 25 years and continue to meet the infiltration and exfiltration requirements of new pipe as specified in AS/NZS1260.1999

Only the DN225 joints exhibit an interface pressure that meets the minimum requirements of the product Standard, AS1260-1984 (Table 2). That is, an initial interface pressure of not less than 0.55 MPa over a continuous length of at least 7mm. All the DN150 joints, except the damaged 00/4, exceeded the interface pressure of 0.4MPa over at least 4mm, as required by the current version of AS/NZS1260. When the joints were disassembled for the interface pressure test, there was no evidence of microbiological attack on the rubber. Nor was there any suggestion of tree root intrusion despite the external staining pattern that implied tree roots were in close proximity to many of the pipes.

All samples of exhumed pipe withstood the flattening test without any cracking or breaking. The flattening test suggests there were no major flaws in the pipe such as weaknesses in the weld lines that are formed in the extruder die-head..

TABLE 2. Interface Pressures for Elastomeric Seal Joints.

Identification	Maximum Interface Pressure MPa	Continuous width with interface pressure higher than :-			
		0.55 MPa	0.4 MPa	0.3 MPa	0.2 MPa
00/1	>0.84	4.7	6.8	8	8.8
00/2	0.8	4.4	7.1	8.2	9.8
00/3	0.74	4.3	6.6	8.9	10.8
00/4	0.8	1.6	2.7	4.8	7.0
00/5	>0.84	8.2	11.8	14.2	15.9
00/6	>0.84	8.8	11.5	13.6	15.0
00/7	0.75	2.8	4.3	5.5	7

The Pipe Stiffness determined for each of the exhumed pipes is shown in Table 3. The results represent the mean of three tests obtained on specimens oriented at 120° to each other. The bending modulus, calculated from the pipe stiffness, is also shown in the Table. As an amorphous material, PVC undergoes physical ageing following the quenching of the pipe in the manufacturing process. This ageing does not involve the breaking of bonds or a change in composition, as occurs in a chemical ageing process. Physical ageing involves a reduction of the free volume within the molecular structure and is accompanied by an increase in strength and modulus. As a consequence of physical ageing, the exhumed pipes are expected to be stiffer than when originally extruded.

TABLE 3. Pipe Stiffness and Flexural Modulus.

Identification	Pipe Stiffness N/m/m	Mean Wall Thickness mm	Modulus MPa
00/1	6047	4.17	3787
00/2	5905	4.19	3644
00/3	7309	4.44	3772
00/4	6834	4.36	3730
00/5	7785	6.98	3943
00/6	8759	7.04	4320
00/6	10350	4.84	4092

The instrumented impact test performed on the pipes is not a standard test but allowed an assessment to be made of the impact behaviour of the pipes. The impact resistance would not be expected to be as good as for new pipes for several reasons. Firstly, the test pipes were likely to have some surface damage as a consequence of transportation, installation and exhumation. Surface damage is expected to provide stress concentrators under impact loading. Also physical ageing results in a slightly denser and stronger material leading to a reduction in the toughness. It can be seen (Table 4) that with all the pipes tested there was a mixture of brittle and no-fracture results. In the case of the new pipes however, the amount of energy absorbed by the specimens that failed in a brittle manner was higher than for the exhumed pipes. This could be attributed to the combined effects of surface damage and physical ageing. Developments in processing and materials could also be a factor in the better performance of new pipes.

The yield strengths varied slightly but the results are consistent with those expected of a non-pressure PVC pipe formulation. There was no difference in the yield strength of the 25 and 16 year old pipes. The DN225 pipes are only 11 years old and had the lowest yield strength. The difference however is not so much due to the age of the pipes but the different formulations. The DN150 pipes have an SG of 1.465 and the DN225 have an SG of 1.522. This indicates the latter is likely to have a higher concentration of calcium carbonate which would cause a lower yield strength and a higher modulus as indicated in Table 5. The yield strain is similarly consistent and appears to be unrelated to age. The stress and strain at break is of less significance as the pipe material has lost its functionality once it is past the yield point. Nevertheless the stress at break appears to vary more with formulation than age. The strain at break varies significantly, being influenced by any flaws or damage in the necked zone of the tensile dumbbell.

TABLE 4. Instrumented Impact Test.

	Wall Thickness mm	Peak Load N	Energy to Break J	Result
00/1	4.07	5400	37.24	Brittle
	4.03	2867	-	Brittle
	4.12	2733	16.27	Brittle
	4.03	5800	40.13	Brittle
00/2	4.01	5400	40.67	Brittle
	4.09	8067		No Fracture
00/3	4.39	7533		No fracture
	4.35	5867		No fracture
	4.42	8400		No fracture
	4.44	6400	46.56	Brittle
00/5	7.16	7600	57.13	Brittle
	6.66	10600		
	6.99	10866		
	7.27	11400		
	7.15	11800	166	Brittle
	6.8	9000	95.5	Brittle
00/6	7.04	9133	107	Brittle
	7.07	11933		No fracture
	6.69	10733		No fracture
	7.11	11800		No fracture
	7.13	10933	137	Brittle
	6.74	10933		No fracture
Contemporary DN150 DWV	Mean 4.19		Mean 115 for brittle results.	6 Brittle 4 No Fracture
Contemporary DN225 DWV	Mean 6.56		Mean 225 for brittle results	2 Brittle 10 No Fracture

TABLE 5. Uniaxial Strength and Elongation.

Identification	Yield Stress MPa	Yield Strain %	Stress at Break MPa	Strain at Break %
00/1	42.2	3.8	37.8	18.3
00/2	43.2	3.8	37.9	28.9
00/3	43.9	4.2	38.9	84.5
00/4	43.0	3.9	39.3	117.2
00/5	39.1	3.8	34.9	56.5
00/6	39.4	3.9	34.9	79.4
00/7	41.7	3.9	36.3	63.8

The gelation properties are set at the time of manufacture and will not have altered in service. The results (Table 6) show a higher level of gelation and higher processing temperature has been achieved with the DN225 pipes than the DN150. The DSC processing temperatures and gelation levels recorded in a second laboratory showed similar trends but were consistently higher. The differences might be due to sampling. It is known for example, the gelation varies through the pipe wall.

TABLE 6. Gelation and processing temperature.

Identification	Heat of Fusion J/g	Percent Gelation %	Processing Temperature °C
00/1	2.0	43	172
00/2	1.7	59	173
00/3	1.8	46	173
00/4	1.5	35	173
00/5	2.4	88	182
00/6	2.4	76	181
00/7	2.2	73	175

The wall thickness of each pipe, measured around the circumference at 45° intervals was plotted against the circumferential position (Fig 6). It can be seen that whilst there is some variation in wall thickness around the circumference, there is no indication that the wall thickness is systematically lower at the invert. Moreover, there is no suggestion of any difference between the pipes of different ages, as might be expected if there was a loss due to wear. Also, all the pipes still comply with the minimum wall thickness requirements of the appropriate product Standard.

RESIDUAL LIFE PREDICTION

The pipe characteristics chosen for determining the quality number are yield strength, bending modulus, wall thickness, joint performance and impact resistance. Because the outcome is influenced by the selection of weighting factors, two series of factors were selected (Table 7), one identified as the "worst case" and the other the "best case". The impact resistance has been given the lowest weighting of 0.1 because, once the pipe is buried, failure by impact is unlikely. Moreover, any change in impact resistance is unlikely to be significant if the pipe is struck by earth moving equipment. The joint performance has been further divided into interface pressure and resistance to infiltration / exfiltration. This has been done because tree root intrusion and leakage represent two different failure modes.

TABLE 7. Weighting factors applied to the "Best Case" and "Worst Case".

Characteristic	Weighting Factors	
	"Best Case"	"Worst Case"
Interface pressure / width of elastomeric seal	0.125	0.1
Bending modulus	0.225	0.15
Impact - Energy to break	0.1	0.15
Yield stress	0.225	0.2
Wall thickness	0.225	0.2
Resistance to infiltration and exfiltration	0.1	0.2

The principle, that values assigned to R_{1-5} can be no less than the measured values M_{1-5}, has been applied. The absence of any deterioration in strength or stiffness implies the ratio $\frac{M}{R} = 1$ for each of these qualities. The contribution of wall thickness to the quality number has been determined by dividing the thickness at the invert by the mean wall thickness. Again the ratio has not been allowed to exceed one. This approach would correctly discriminate against pipes in which abrasion was significant and loss of wall thickness a possible failure mode. It is not possible to determine whether the joints have deteriorated, only that they are not leaking and, except in one case, still satisfy the interface pressure requirements of the current Standard. The Quality Number for these pipes therefore exceeds 0.8 to beyond 120 years and according to the rating system used by Sagrov, the pipes are judged to be good, showing effectively no evidence of degradation.

The Quality Numbers for the exhumed pipes versus the number of year's service, are shown in Fig. 7 (a). The graph shows the minimum life expectancy of the PVC pipes tested to be in excess of 98 years. The "best value" weighting factors give a more optimistic predicted service life of almost 300 years. It should be noted that the number of samples tested is only seven and the program should be continued in order to predict the life expectancy with an even greater confidence.

Linear multivariate regression analysis has been applied to the test results and an alternative prediction of service life determined (Fig. 7 (b)). In this analysis, the ratios of *Measured Parameter:Reference Value* for the characteristics in Table 7 were used as independent variables and linear multiple regression analysis was undertaken with *Age* as the dependant variable. This analysis supports the outcome of the judgemental analysis.

CONCLUSIONS

- Seven exhumed pipes have been tested for a range of physical characteristics. The pipes from Ipswich varied in age from 11, 16 and 25 years according to the print messages that were still quite legible. The age of the pipe exhumed from Winmalee is estimated to be 20 years.

- There was no evidence of any erosion of the pipe wall during service and this would not seem to be a limiting factor in the life of these pipes.

- All of the elastomeric seal joints were free of tree root intrusions and there were no signs of degradation of the seals themselves. The joints were sound and functioned well enough to meet the requirements of the current DWV Standard. The interface contact pressures remain high and meet the current Standard. However, only the DN225 pipes still meet the contact width specified in the superseded sewer pipe standard from 1984.

- The stiffness of the pipes has, if anything, increased with time as result of physical ageing. Most of the increase in stiffness from the effects of physical ageing has already occurred for the exhumed pipes. Little further increase in stiffness can be expected.

- Similarly, the yield strength would have increased somewhat with time but further increases will not be substantial.

- There appears to be some reduction in the impact resistance of the pipes but this is of little consequence whilst the pipes remain undisturbed. Without being subjected to any more surface damage or significant increases in strength due to ageing, the impact resistance is not expected to change further.

- Overall, there is no evidence to suggest the pipes will have their service life limited by erosion of the wall or changes to the strength or stiffness of the material. Moreover, the joints continue to not only function, but also meet the requirements applied to new pipes. There is nothing in the test results to suggest the life of the pipes will be limited to 50 years. Given the pipes have been in service for 25 years and are in such good condition, there is no reason to suppose they will not achieve upwards of 100 years service.

- The Quality Number approach suggested by Sagrov for application to concrete pipes has been adapted for PVC and confirms there has been no significant deterioration in the pipes. The method needs further refinement in that an extremely low value for a critical characteristic should not be able to be over-ridden by all the other characteristic, however good they remain.

- Multivariate statistical analysis of the test data confirms the PVC sewer pipes are expected to have service lives in excess of 100years.

Figure 1. Sulphide staining at invert.

Figure 2. Damaged Sample 00/4.

Figure 3. Distortion in spigot of 00/4.

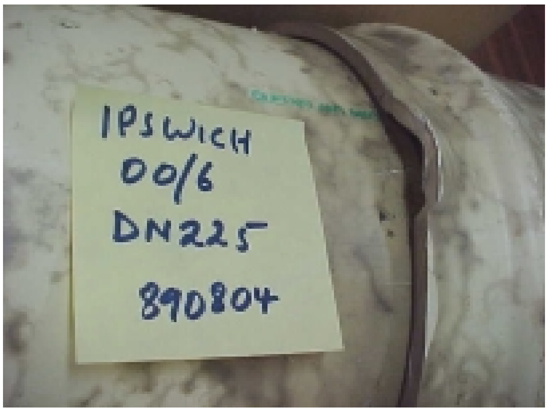


Figure 4. Damage to socket of 00/6.

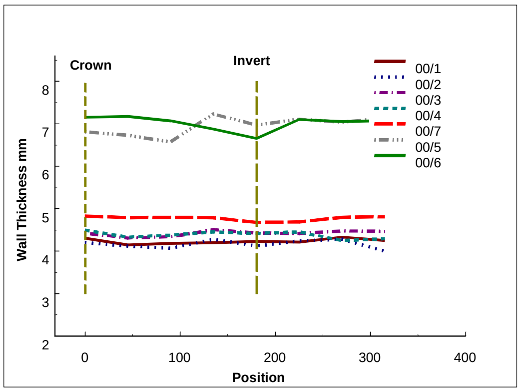
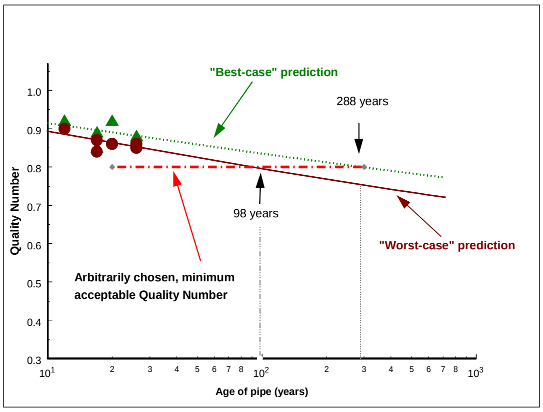


Figure 5. Typical external staining pattern. Figure 6. Wall thickness of individual pipes.



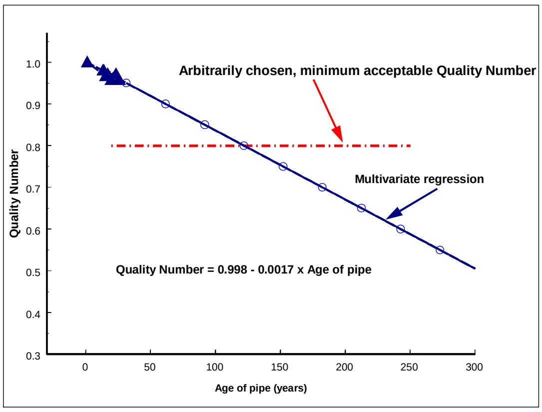


Figure 7 (a) Judgemental approach. Figure 7 (b) multivariate regression. analysis.
Quality Number versus Years of Service.

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