LONG TERM PERFORMANCE OF PVC PRESSURE PIPES IN A LARGE RURAL WATER SUPPLY SCHEME

M. W. Stahmer [1] and A. J. Whittle [2]

[1] Vinidex Pty Ltd, Australia. [2] Iplex Pipelines Australia Pty Limited.

ABSTRACT

A number of PVC pressure pipes were exhumed from a large rural water supply scheme constructed in the early 1970s. The pipes had been extruded by three manufacturers in both elastomeric seal and solvent cement joints. The pipes were subjected to a range of mechanical tests in order to assess whether there had been any deterioration during their service. The material properties were found to be similar to contemporary production. These results, in conjunction with an assessment of the scheme's operating conditions, indicate the pipes should continue to provide satisfactory service for many years.

INTRODUCTION

Poly(vinyl chloride) (PVC) pressure pipes have been used for water reticulation in Australia for over thirty years. The potential life remaining in a particular pipe system, and the value of the asset, is of major interest to the owner of the facility. Quantifying how long a pipe will remain serviceable is sometimes complicated by misunderstandings surrounding the characteristics of PVC pipes.

As a viscoelastic material, PVC exhibits time dependent properties under stress. Unfortunately this time dependency is sometimes interpreted as age dependency. For example, the down-ward slope of the traditional pipe hoop-stress regression curve is often interpreted as a loss of strength with age. In fact the down-ward slope simply reflects the ability of the viscoelastic material to support lower stresses for longer periods than it can support higher stresses. Hucks (1) demonstrated the burst strength of PVC pipes was not diminished by long term exposure to lower stresses. The burst strength was shown to be higher for pipe aged in the laboratory for 10 years than it was for the same pipe at the time of manufacture. The pipes were aged under stresses equal to one of two times the design stress.

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 stiffness. Physical ageing provides an explanation for the increase in short - term strength observed by Hucks.

A number of studies have been made of exhumed PVC pipes in order to test the premise that material degradation is neither occurring nor adversely affecting potential service life. Lancashire (2) studied PVC water pipes exhumed after 4 to 16 years' service and concluded that ageing was not a significant factor influencing the performance of the pipes. Material quality, particularly good gelation and small size of inclusions, was found to have the overwhelming influence on performance.

Bauer (3) tested PVC sewer pipe exhumed after 15 years service and reported no measurable degradation of the material in this period. In particular it was reported that there was no embrittlement and no decrease in modulus or pipe stiffness.

Alferink et al (4) tested exhumed PVC pressure pipes ranging up to 37 years of age. It was concluded that there was virtually no change in the mechanical properties of the pipes due to ageing. It was also observed there had been a continual improvement in pipe production, especially gelation during the extended period over which the pipes in this study had been made.

Studies of the field failure rates of PVC pressure pipes have also been made. Kirby (5) compared the failure rates of PVC and cast iron pipes in the U.K some 18 years after the former was first adopted for water reticulation and pumped sewerage applications. There was no suggestion of an increasing failure rate as a consequence of ageing. On the contrary, a decreasing failure rate was reported for the PVC pipes with the passing of time. In particular a significant improvement occurred in the performance of PVC pipes after 1973. This coincided with the publication of the British Code of Practice CP312 which provided detailed instructions for the storage, transport, installation and backfilling of plastics pipes.
Bjorklund (6, 7) investigated failure rates of PVC in water distribution systems in Sweden. The better performance of pipes made after 1973 was attributed to significant improvements in pipe quality as a result of using higher K-value resin and achieving higher gelation levels.

Given the interest of Australian water utilities in the residual life of PVC pipe systems, an exhumation and test programme was undertaken. The water scheme selected for the exhumations was constructed in the early 1970's. The manufacturing dates of the pipes therefore straddle the period during which Kirby and Bjorklund reported improved PVC pipe performance in the U.K. and Sweden respectively. Pipes made by the three manufacturers operating in Australia at the time were included in the project.

THE WATERWORKS SCHEME

The Millewa Waterworks District Scheme, in North Western Victoria, was a major project undertaken to replace an open channel domestic and stock water distribution system with pipelines. The system to be replaced comprised a pumped supply from the River Murray into an open channel to Lake Cullulleraine. From Lake Cullulleraine the water was delivered by an open channel system, with further relift stations, to earthen storages on 126 farm holdings.

Approximately 5% of the water entering the channel system at the River Murray pumping station became available for use on the farms, the remainder being lost through seepage and evaporation.

Following a State Government Inquiry in 1965, the program to replace the open channels with a closed pipe system was approved, and construction commenced in 1970.
As a consequence, water was reticulated through 644 km of pipelines serving the 126 holdings and two urban locations spread over a total area of 227,000 hectares.

In addition, as part of the project, approximately 500 km of on-farm pipes were laid from the meters to sealed holding storages. Funding of the project was by a combination of State Government loans and Federal Government grant.

After almost 30 years of successful operation, samples of PVC pipe were exhumed for testing, the purpose being to determine whether there had been any deterioration in the quality of the pipes during their service life. This scheme was selected for the exhumation project because it represented a large reticulation system and it was known that comprehensive installation and operational records had been retained.

DESIGN AND CONSTRUCTION

The State Rivers & Water Supply Commission (SR&WSC) carried out all design work and project management for the construction of the scheme.

The climate in the Northern Mallee district of North Western Victoria is such that consideration had to be given to possible elevated ground temperatures for determination of the appropriate pipe pressure classes. The CSIRO, Merbein Office, reported peak ground temperatures, at a depth of 20" (500mm) below the surface, ranging from 55°F (41.5°C) in August to 80°F (27°C) in February. It was considered that, at 30" (760mm) minimum depth, no special provision needed to be made for elevated operating conditions. That is, ground temperature would not be a limiting factor in the use of PVC. However, the sporadic rainfall conditions and the nature of the native soil necessitated consideration of the effects of potential ground movement. Accordingly, only plastics pipes, with their inherent flexibility, were considered in sizes below 8" diameter.

With the exception of some pipelines installed by SR&WSC day labour forces, pipelines were constructed on a "supply and install" basis by contractors selected by the SR&WSC.

Pipes used in the project were of either PVC or asbestos cement (AC).
Concrete pipes were considered unsuitable due to pressure restrictions, whilst polyethylene pipes were not an economical proposition at the time.
The use of AC pipes was restricted to diameters 200mm (8") and above due to concerns about the beam strength being sufficient to cope with possible ground movement.
There were no limitations placed on the use of PVC, which was subsequently installed in sizes from 20mm to 200mm. (3/4" to 8").

Pipe pressure classes ranged from Class 4.5 to Class 18 (‘A’ to ‘F’ under the now defunct classification system). Pressure classes were selected solely on the basis of the internal working pressure of the particular part of the system they were destined for. There was no adjustment to the pressure class of pipes for the many rail and road crossings. The latter included both sealed and unsealed roads.

Pipe lengths were generally 20ft. (6m). However, for one contract, incorporating all sizes up to 8", solvent cement jointed 34 ft. (10m) lengths were used.

The fittings and appurtenances included air valves, isolating valves, fire plugs (used for scour outlets), and metered services.

Fittings types used in the system were moulded PVC pressure fittings, coated aluminium, wrapped cast iron gibaults, flanges and tees together with cast iron and brass valves.

UPVC PIPES SPECIFICATION & MANUFACTURE

PVC pipes and fittings were manufactured to Australian Standards ASK138:1967 Rigid PVC Pipes for Pressure and Non-pressure Applications, ASK138:1969 Rigid PVC Pipes for Pressure and Non-pressure Applications, and AS1477:1973 Unplasticized PVC Pipes and Fittings for Pressure Applications, as appropriate. However, the specification used for most of the PVC pipes was ASK138:1969.
During manufacture pipes were routinely tested for resistance to flattening, impact resistance at 0°C and 20°C, resistance to acetone and sulphuric acid, reversion, softening point and resistance to internal hydrostatic pressure.

The PVC pipes were manufactured by Vinidex Tubemakers, Hardie Extrusions, and Hume-S-Lon at sites specifically approved by SR&WSC.
The PVC resins used in these pipes were produced by I.C.I. Australia for Vinidex, BF Goodrich (Aust) for Hardie Extrusions, and Sekisui (Japan) for Hume-S-Lon.
Whereas Vinidex and Hardie Extrusions produced their own dry blends, the Sekisui material was fully precompounded.
As the pipes were lead stabilised, the SR&WSC took samples of water from the system for lead testing shortly after commissioning the first major line in 1971. The concentration of extracted lead in the samples was below the limits of detection.

Joint types used for PVC pipes were elastomeric seal (rubber ring, RRJ) and solvent weld (SWJ), with both types of joints being used in sizes up to 200mm. However, the use of SWJ was minimal by comparison with RRJ. The rubber ring joint designs were as used to this day by Vinidex and Iplex Pipelines. Rubber rings, as now, were manufactured from natural rubber compounds.

INSTALLATION

General
Installation, including handling and storage, pipelaying and jointing, and pressure testing, was in accordance with SR&WSC specifications. These specifications were subsequently incorporated into Australian Standards AS CA67:1972, and AS 2032:1977. Pipes were installed with a minimum of 750mm cover, increasing to 900mm at road and rail crossings.

Trench Conditions
Pipes were surrounded by granular material obtained from the excavation or, in the case of rock excavation, from nearby. A layer of granular material was placed beneath the pipe to a minimum depth of 75 mm throughout the project, including areas of rock excavation.
Typical trench conditions are illustrated in Fig. 1.

Jointing
Whether RRJ or SWJ were used was determined by the “in-ground’ cost. Both solvent cement and elastomeric seal systems were approved by the principal. Rubber ring joints were to the SR&WSC specification. The specification required the spigots to be inserted into the sockets

of elastomeric seal joints to a witness mark that allowed for subsequent thermal expansion. In practice, the spigots were generally inserted past the witness mark.
Elastomeric seal joints as exhumed and subsequently sectioned are depicted in the Fig. 2. Dark staining is evident on the matching socket and spigot surfaces where the water was essentially dormant. This is likely to be due to sulphides reacting with the lead stabiliser in the pipe. The staining is only a surface affect. There was no evidence of loss of elastomer due to microbiological attack.

Solvent weld sockets were manufactured to have an interference fit with the spigot. It was reported that some solvent weld joints leaked when the lines were first pressure tested. This was attributed to poor workmanship during installation rather than the quality of the pipes supplied.

Solvent cement jointing for pipes up to 8" dia. was conducted to the SR&WSC specification using appropriate cements for the products and environment, plus disposable brushes and containers. These pipes were usually jointed above the trench and lowered into the trench the following day.

Pressure Testing
Pipelines were tested to 1.3 times nominal working pressure of the pipe, the time of test being varied from two hours to 24 hours, depending on the length of pipeline under test.

Figure 1. Trench Conditions

Figure 2. Typical RRJ

PERFORMANCE

The first pipeline was put into service in 1970, with subsequent sections being commissioned as they were completed. The project was completed in 1975. Sunraysia Water Corporation, the current operator of the system, has reported the following:

AsbestosCement. - AC pipe joints have been reported as leaking and subject to tree root intrusion. Pipe barrel failures due to ground movement have occurred.

PVC - No reported leaks in either elastomeric seal joints or solvent weld joints, with the exception of one 40mm solvent weld joint failure. The cause of this single failure is not known. However, it has been revealed that solvent weld joints in one particular spur line have been leaking sporadically over an extended period. This spur consists of 1,230m of 4" PB (DN100, PN6) pipe., operating at heads up to 180 ft (55m). At the time of installation, this pipeline suffered joint leaks during field pressure testing, to the extent that many attempts were made before a successful test was achieved. The test pressure was 260ft. (80m) head. The presence of ground seepage, rather than catastrophic failure of the joints, has indicated occasional leaks ever since. The cause of these joint problems is to be further investigated.
No pipe barrel failures have been reported, other than those resulting from third party damage.

Valves and Fittings - Corrosion has occurred with some valves.
Air valve blockages due to ants have been reported.

Water Quality - As mentioned above, the possibility of lead extraction adversely effecting the water quality was investigated and discounted early in the project.
Some pipelines are currently "contaminated" by a grey sludge [fig. 3]. This material is thought to be at least partly composed of dead organisms and has had no apparent effect on the performance of the PVC pipes.

Figure 3 Sludge from the bottom of the pipe.

EXHUMATION AND TESTING

The prime objective of the pipe exhumation project was to determine, by physical testing, whether there had been any deterioration in either the PVC pipes or joints. This assessment to be made in conjunction with reports of operational performance.
The field performance of the PVC pipes has been excellent, as described above.

The pipes were exhumed in 1996, after approximately 25 years of service [table 1].

The exhumed pipes were subjected to a range of tests to determine whether they had shown any signs of deterioration and to assess their quality compared to contemporary pipe production. Unless otherwise specified the tests were performed at 20 ±2°C.

Manufacturer	Diameter and Pressure Class	Specification	Joint Type
Vinidex	2" Class PD	ASK 138:1969	RRJ
Vinidex	4" Class PC	ASK 138:1969	RRJ
Hardie Extrusions	4" Class PD	ASK 138:1969	RRJ
Hardie Extrusions	6" Class PC	ASK 138:1969	RRJ
Humes Plastics	6"Class PD	ASK 138:1969	RRJ
Humes Plastics	8" Class PB	ASK 138:1967	SCJ
Humes Plastics	4" Class PD	ASK 138:1969	RRJ

Table 1. Details of Exhumed Pipes.

1. Resistance to flattening was carried out by placing short sections of pipe between parallel plates and deflecting to 40% of the original diameter at 20°C. The sections were then inspected for any damage or fracture. Test Method: Australian Standard AS 1462.2

2. Resistance to impact was performed using a mass, falling through 2m at 20°C. A failure being recorded if there was any fracture evident in the specimen at the conclusion of the test. The size of the mass varying with the size of the pipe in the manner described in the product Standard. Test Method: Australian Standard AS 1462.3

3. The gelation level was measured using the method described by Potente and Schultheis (8) and Gilbert and Vyvoda (9). The melt temperature, heat of fusion and percent gelation were determined. The percent gelation being calculated by dividing the area of the secondary crystallisation endotherm by the total area of the primary and secondary endotherms. The melt temperature was recorded as the point of inflection between the two endotherms.

4. The dispersion of the resin in the pipes was assessed on microtomed samples approximately 0.02 mm thick under low power magnification.

5. Tensile properties of the PVC were determined on four pipe samples, using the average of five determinations for each. Test Method: ASTM D638M-1991.

6. The fracture toughness of the pipes was determined using the notched C-ring method. For each of the pipes tested, a series of c-rings was prepared and tested under a range of applied stresses. The stress and time to failure was recorded for each. The fracture toughness versus the time to failure was plotted. The fracture toughness K_{1c} at 15 minutes was calculated [Table 2]. Test Method: Australian Standard Draft No. 2570.

RESULTS

Resistance to Flattening and Impact

The number of impact tests performed varied with the amount of pipe available. In some cases, for example Vinidex 4" PC, the samples of the pipe were tested in more than one laboratory.

Pipe Identification	Flattening		Impact	
	Passes	Failures	Number of Strikes	Number of Failures
Vinidex 4" PC	8	1	17 2 3	6 2 2
Hardie Extrusions 4" PD	2 (repeat 3)	1(repeat 0)	24	0
Humes Plastics 4" PD	3	0	6	0
Hardie Extrusions 6" PC	2	0	24	7
Humes Plastics 6" PD	2 (repeat 3)	1(repeat 0)	26 3	4 1
Humes Plastics 8"PB	2	0	34	1
Vinidex 2" PD			2	2

Table 2 Results of Flattening and Impact Tests.

Gelation

The percent gelation, heats of fusion and melt temperatures are shown in Table 4.

Pipe Identification	Percent Gelation	Heat of Fusion J/g	Melt Temp. °C
Humes Plastics 6" PD	44	1.9	185
Humes Plastics 8" PB	48	1.9	183
Hardie Extrusions 4" PD	44	2.3	175
Humes Plastics 4" PD	54	2.2	183
Hardie Extrusions 6" PC	64	2.7	183
Vinidex Tubemakers 4" PC	60	3.5	181

Table 4 Results of Thermal Analysis by DSC

Dispersion

The polymer dispersion (residual structure of the PVC grains), was judged by comparing microtomed sections with in-house, reference photographs used by the Australian PVC pipe manufacturers. The results were variable and generally not as good as current production [figure 4].

Tensile Properties

The uniaxial tensile strength at yield and at break, together with the elongation at break are shown in Table 5.

Pipe Identification	Tensile Strength at Yield (MPa)	Tensile Strength at Break (MPa)	Elongation at Break (%)
Humes Plastics 4" PD	51.4	35.1	31.4
Vinidex 2" PD	49.7	36.4	30.8
Hardie Extrusions 6" PC	50.0	31.4	36.8
Humes Plastics 8" PB	50.8	31.5	34.7

Table 5. Uniaxial Tensile Strength and Elongation at Break.

Fracture Toughness

The fracture toughness versus time-to-failure results were plotted [fig 5]. The fracture toughness at 15 minutes ranged from 4.2 to 5.1 MPa $m^{1/2}$ for the four pipes tested.

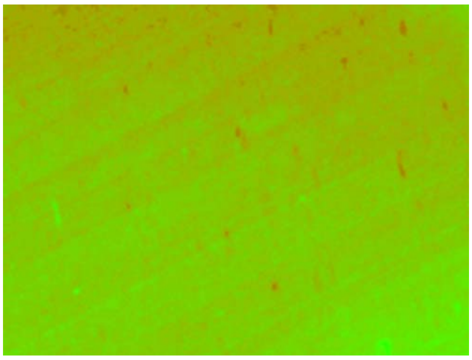

Figure 4. Dispersion of Humes 8" Pipe

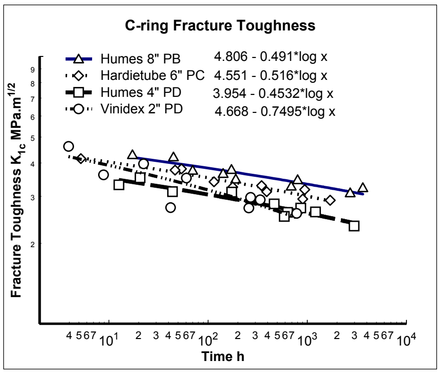

Figure 5 C-ring Fracture Toughness

CONCLUSIONS

The PVC pipes and joints in the Millewa water scheme in North Western Victoria are performing well, having been in service for almost 30 years. The pipes were installed in a variety of terrains including sandy soil and solid limestone. The performance has been satisfactory in all situations. In addition, the pipes in the system traverse both roads and rail lines. In neither instance was the pressure class of the pipe upgraded to accommodate the dynamic loads imposed by passing road traffic or trains. Nevertheless, no failures have been reported as a consequence of dynamic loading. The long-term performance of the system has been clearly dependent upon the initial pipe quality, handling and installation. Degradation of the PVC material has not occurred.

For the four pipes tested, the tensile strength at yield and elongation-at-break were essentially the same. Moreover, the results are the same as expected for contemporary pipes tested at the time of manufacture. Thus it can be concluded there has been no degradation in the strength or elongation characteristics of the PVC during the service life of the pipes. The exhumed pipes have not suffered any loss of strength as a consequence of operating under pressure for almost 30 years.

The fracture toughness of all the samples tested was much higher than the values reported by Lyall (10) and J. M. Marshall et al (11) for pipe made in the UK at about the same time. In addition, the fracture toughness was comparable to, or exceeded, the value now expected for well-processed PVC pressure pipes. These results imply there has been no deterioration in the fracture toughness during a service life approaching 30 years.

Some variability occurred in the impact test results but this did not appear to be related to a particular manufacturer, pipe size or pressure class. The variability is possibly due to surface damage caused during the exhumation, transport or original installation. Weathering of the pipe during the storage and transport period might also have contributed to the variability of the impact resistance. The field performance of the pipeline has not been adversely affected by such surface damage.

Flattening test results on the exhumed pipes were also variable and again it is possible surface damage could be a contributing factor.

The degree of gelation and the quality of the dispersion would be expected to be higher with contemporary PVC pipe production. Nevertheless, the performance of the pipes has not been adversely affected by these factors.

The findings of this investigation support the earlier works by Lancashire, Bauer and Alferink et al.

Acknowledgments.
The tests were performed at –
Vinidex Tubemakers Pty. Ltd., Sunshine, Vic.
Iplex Pipelines, Technical Centre, Gladesville, NSW,
Australian Vinyls Corporation, Ascot Vale Victoria.
CSIRO DBCE, Highett, Victoria (C-ring fracture toughness).
The assistance of the staff in performing the tests at these facilities is appreciated.

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