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VALIDATION OF THE LONG LIFE OF PVC PIPES

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ABSTRACT

Several analytical studies have estimated that PVC pipe can have a useful life of over 100 years. The earliest widespread use of PVC pipes was in Germany in the late 1930's. These early pipes lacked proper extrusion technology. Extrusion technology was greatly developed during the 1950's and 1960's. Use of PVC pipe in the USA started in the early 1960's. It was desired to try to validate the expected long life of PVC pipe. Recently, Utah State University conducted several tests on PVC pipes that had been in use between 20 and 49 years. The tests conducted include acetone immersion and burst pressure or hydrostatic integrity tests. The purpose of these tests was to examine if the pipe still met the quality control standards that were in place when they were manufactured. The results show that when the material has proper gelation, all of the quality control tests were successfully passed. This paper will also review these test results along with testing done by other researchers examining the long life expectancy of PVC pipe.

INTRODUCTION

In the United States and Canada, underground water infrastructure was installed during three main time periods because of the population growth in the 1800s, 1900–1945, and post 1945. Pipes made of iron constructed in each of these three eras will all start to fail at nearly the same time over the next couple of decades due to the corrosion of the iron pipes. Additionally, the life span of the materials used since the 1960's has changed. Grey cast iron pipes are no longer manufactured and the new ductile iron material has been made thinner to reduce costs, but as a result, the pipe life expectancy has become shorter with each new investment cycle (1). In 2013, the American Society of Civil Engineers issued a USA Infrastructure Report Card and gave an overall "D" grade to drinking water and wastewater infrastructure which included the piping infrastructure. In an update to the "Dawn of Replacement" (2), AWWA has published "Buried No Longer" which states "More than a million miles of pipes are nearing the end of its useful life and approaching the age at which it needs to be replaced" (3). These water pipe replacement costs combined with projected expansion costs will exceed $1 trillion over the next couple of decades. The cost of underground pipe infrastructure is only 60% of the US water industry's total funding requirement. In additional, sewer and storm drain funding needs also drive up the cost burden on rate payers. Municipalities continue to struggle with balancing water service affordability against the rise in service interruptions and declining water quality. With the introduction of piping materials such as PVC, utilities were able to address the issue of iron pipe degradation due to corrosion.

Infrastructure asset management is an approach which can help utilities bring together the concepts, tools, and techniques to manage assets at an acceptable service level at the lowest life-cycle cost. Asset management practices applied to underground infrastructure help utilities understand the timing and costs associated with replacement activities. The knowledge gained from these efforts also helps in the development of effective pipe material selection through comparative financial analysis called "life cycle costing" as part of the replacement strategies and funding plans. Understanding the longevity of a pipe improves the ability for management to make better infrastructure investment decisions with improved affordability results for customers.

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THE AFFORDABILITY ISSUE

Traditionally, there has been a lack of analysis which would combine both underground pipe performance and affordability. Existing practices tended to ignore the effect of environmental conditions on different pipe materials. Yet, every engineer understands how the complexity of underground infrastructure has increased along with the array of choices. The ability to change old habits and consider new materials requires additional analysis, and improved design and installation practices. This enhanced analysis of pipe design, selection and installation sets forth the longevity and life-cycle costs critically influencing water service affordability for the next 100-200 years.

There have been many studies on water main failures rates in the US, Canada, Australia, and Europe over the last three decades. These studies mainly compared the number of pipe breaks by general pipe type and by length. While these studies have been very helpful to the water industry, the new driver has been concerned with the ability to make underground pipe decisions to improve the repair and replacement costs in an effort to address the affordability of water services to customers. This new level of fiscal accountability and demand for transparent utility management back to their owners and stakeholders has increased the need of additional evidence to demonstrate the improved decision making. Dig-up reports and pipe performance and longevity studies form the next body of evidence needed to collaborate water main break surveys and studies.

The simple formula in a life cycle cost framework is essentially that “a pipe which has a long life at a low cost is the most affordable.” Engineers are to make available every alternative which would answer the simple question of longevity and cost at each relevant point within the underground network providing service. A key issue in the life cycle cost framework is the expected life of a pipe. Clark, et al (4) presents an analysis of a single utility in Laramie, Wyoming that would indicate that initially the survival probability of a PVC pipe is much lower than for a ductile iron pipe. That conclusion is at odds with a survey by Folkman et. al. (5) of 188 utilities across the US and Canada showed that PVC pipe has the lowest overall failure rate when compared to cast iron, ductile iron, concrete, steel and asbestos cement pipes. One very important conclusion from Folkman et. al. is that failure rates vary widely between utilities and thus drawing conclusions from the results of one or a few utilities is not recommended.

The analysis of pipe breakage is incomplete without the assessment of why the pipe failed. This knowledge is then applied to the cost analysis of repairing and replacing the pipe. Once again, analysis would dictate that if a pipe is failing in less than 100 years then one or more of the following factors should be considered; a) the pipe has identified manufacturing defect, b) the recommended installation procedures were not followed, c) the design process did not correctly address the actual operating conditions, and/or d) the pipe material originally selected needs to be changed. The 2013 United States Conference of Mayor’s report on Municipal Procurement (6) highlighted the importance of such procurement policies.

WATER MAIN BREAK STUDIES

Water main break studies over the last 30 years demonstrate the changing trends based on the use of various pipe types.

- In 1981 Kirby (7) published an early study of water main failure rates in England. Kirby noticed that first PVC installations in 1965 suffered from higher failure rates than cast iron pipes. Most of these failures were related to improper installation procedures. By 1979, the failure rates of PVC had dropped to well below that of cast iron due to improved pipe installation procedures.
- In 1981 Bjorklund (8) looked at water main failure rates in Sweden. He noted the improved performance of PVC pipes.
- In 2005 Burn, et. al. (9) conducted a small survey of water utilities in Australia, Canada, and US. Important observations include the low overall failure rate of PVC relative to other pipe materials. Variability in survey data indicated that early failures were very likely attributed to installation practices.
- As previously mentioned, the 2012 US Water Main Breaks Study by Folkman, et. al. (5) reported results of a survey of 188 utilities across the US and Canada. That survey demonstrated that PVC pipe has the lowest overall failure rate when compared to cast iron, ductile iron, concrete,

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steel and asbestos cement pipes. Corrosion was indicated as the primary cause of failure. PVC currently represents about 23% of the total length of pipe installed in US water systems. PVC dominates the rural water systems and the sewer underground infrastructure. The report also found that 8.4% of water mains are described as beyond their useful life. The average age of failing water mains is 47 years.

THE DIG-UP REPORTS: EVIDENCE OF PERFORMANCE AND LONGEVITY

Dig-up reports have occurred globally, but mainly occurring in Australia, Europe, Canada and the United States. In these reports, the pipes were subjected to a range of mechanical tests in order to assess whether there had been any deterioration during their service. Dig-up reports are valuable because they show results from pipe installed by contractors and in use for decades. Laboratory testing has a difficult time simulating real world installation and operation conditions.

UNITED KINGDOM AND EUROPEAN STUDIES

In 1985, Lancashire (10) investigated whether the performance of PVC-U pipe is affected by time in service. Lancashire 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. The pipes were 4 inch, Class C (operating pressure 9 bar) from a single manufacturer. They performed stress regression testing and concluded that initial pipe quality is the overriding influence in determining pipe performance. All of the pipes tested would be expected to exceed a 100 year life under normal operating conditions.

In 1996, Alferink et al (11) tested exhumed PVC pressure pipes ranging up to 37 years of age. It was concluded there was virtually no change in the mechanical properties of the pipes due to ageing. The report summarized results of testing a total of 19 pipe samples. The tensile tests showed that the material modulus does not decrease with pipe age. There did not appear to be any changes in tensile strength and impact strength with pipe age. Stress regression testing showed that PVC pipes after 35 years of service still were meeting CEN stress regression requirements. They concluded that "old PVC water pressure pipes still fulfill the most important functional requirements. Ductility and resistance to internal pressure have been virtually unaffected by ageing, and are still on the same level as for new pipes."

Hülsmann (12) in 2004 reported on tests of some of the first PVC pipes installed in Germany. One set of tests examined 15 pipe specimens were exhumed after being in use for 23 years. They ranged in diameter from 20-48 mm (0.787-1.890 in) and were subjected to long term hydrostatic pressure testing. The testing was completed at 60°C and then the Arrhenius equation was used to scale the results back to 20°C. The extrapolation of the stress regression data was taken out to 10^6 hours (114 years). Hülsmann concluded that under realistic conditions in the Bitterfeld location and at 4-5 bar (58-83 psi) water pressure, it may be assumed that another 100 years of safe operation could be expected. An additional nine pipe specimens, 4 coming from a 32.5 mm (1.28 in) pipe and 5 coming from a 25.2 mm (1.0 in) pipe, were in operation as potable water pipes for 53 years at 4-5 bar (58-83 psi) operation pressure. The 9 samples were subjected to long term hydrostatic pressure test at 60°C. An extrapolation of the stress regression data was to 10^6 hours (114 years). In conclusion, these pipes would last another 100 years of operation even at 7 bar (102 psi) and 60°C (140°F) operating conditions. If the temperature is between 20-40°C (68-104°F) and the operating pressure is doubled to 8-10 bar (116-145 psi), the pipe would easily operate for 100 years as a potable water pipe with a safety factor of 1.5.

The following year in 2005, Boersma and Breen (13) examined chemical and physical ageing of PVC pressure pipe. They defined chemical ageing by a change in the chemical structure of a polymer and physical ageing as a change in the physical structure. He notes that "Chemical ageing at 15°C seems not to have a significant influence on the quality of PVC water distribution pipes." Physical ageing was investigated by examining the free volume relaxation by measuring yield stress. Accelerated aging of PVC pipe at 60°C leads to an increase in yield stress and thus yield stress is an indication of the pipe age. However, measured yield strength of pipes in service up to 30 years does not show any trends indicating changes in yield strength with pipe age. He concluded that "Physical ageing at 15°C seems not

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to have a significant influence on the quality of water distribution pipes." They also tested PVC pipes for craze initiation, stress regression, slow crack growth, and fatigue and concluded that the service life of high quality PVC should exceed 100 years.

In 2006, Breen (14) studied five excavated pressure pipe specimens produced between 1959 and 1997 with pipe diameters between 160 and 400 mm (6.3 and 15.7 inch). He performed chemical and physical ageing tests on the PVC along with tensile, craze initiation, burst test, slow crack growth, impact test, and fatigue measurements. He concluded that the "existing PVC tap water pipe systems in the Netherlands will operate for at least 100 years provided that the internal and external loads do not result in hoop stresses which will exceed 12.5 MPa and that no micro-crack and mechanical damages are present in the PVC pipes."

AUSTRALIAN TESTING SHOWS NO PIPE DEGRADATION AFTER 30 YEARS

The testing methodology used by Stahmer and Whittle (15) takes into consideration the field performance of the PVC pressure pipes as well as the actual testing based on the Australian Standards. The pipes which were exhumed in 1996 after 25 years of operation were subjected to the following tests:

- Resistance to flattening per Australian Standard AS 1462.2
- Resistance to impact per Australian Standard AS 1462.3
- The dispersion of the resin in the pipes was assessed on samples approximately 0.02 mm thick under low power magnification.
- Tensile properties of the PVC were determined on four pipe samples, using the average of five determinations for each.
- The fracture toughness of the pipes was determined using the notched C-ring method per Australian Standard Draft No. 2570.

It was reported that these PVC pressure pipes were installed in a variety of terrains including sandy soil and solid limestone. The performance was reported to have 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.

These results imply there has been no deterioration in the fracture toughness during a service life approaching 30 years. 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. The findings of the Australian pipe testing support the earlier works by Lancashire (10), Alferink et al (11) and Bauer (16).

Numerous studies on the fatigue failure characteristics of PVC pipe have been conducted. In 2005 Whittle and Teo (17) summarized previous research and conducted rotating beam experiments with notched PVC specimens and were able to match fatigue failure test results from pressure cycling PVC pipes. Their results show that an endurance limit exists in PVC-U pipes such that stress amplitudes less than 2.5 MPa (362 psi) would have negligible effect on the life of a pipe. This stress range is well below that expected in a typical municipal water system.

The Water Research Foundation funded a study published in 2005 titled "Long-Term Performance Predictions for PVC Pipes," Burn, et. al. (9). This report is a comprehensive review of methods to analyze the expected life of PVC pipe. They report that 100 years is a conservative estimate for a "properly designed and installed pipe." A survey was sent out to 44 water utilities in Australia, Canada, and the USA. Of the 44 participants, 17 water utilities provided detailed data. Fracture mechanics-based

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models were produced to predict the conditions under which pipe failure will occur in service. These models were calibrated against failure rates recorded in several North American and Australian utilities.

NORTH AMERICAN STUDIES

Moser and Kellogg in 1994 (18) published a AWWARF funded survey of water utilities and performed impact and acetone immersion tests on 59 PVC pipe samples from 16 different utilities that were being installed in 1992. The samples provided came from ten different PVC pipe manufacturers. All of the samples passed the acetone immersion test and only four samples failed the impact tests. The survey results found some evidence of early PVC pipe failure but these problems usually occurred in the first year of operation and were usually attributed to improper pipe installation.

Moser and Folkman (19) reviewed previous studies of fatigue failure in PVC pipe and guidelines to prevent failures. They also conducted numerous pressure cycling tests of 6-inch PVC pipe and combined their results with previously reported data.

In 2013, EPCOR's Seargeant (20) reported on water main breaks in the system in Edmonton, Canada. The highly corrosive soil in Edmonton necessitated a transition from cast iron to asbestos cement pipes in 1966 and then to PVC starting in 1977. The transition to PVC has produced a dramatic reduction in water main break rates for the city. EPCOR also demonstrated that a PVC water main could be frozen in winter and not burst. This evidence is critically important for geographic areas facing climate change with severe winter conditions and freezing storms and flooding. Three PVC pipes were excavated and tested. One pipe had been in service for 17 years and the other two had been in service for 25 years. Quality control tests including quick burst, impact resistance, flattening, and acetone immersion were completed and the tests demonstrated the pipe met virtually all new pipe requirements.

RECENTLY COMPLETED DIG-UP TESTS

In 2013, Folkman and Barfuss (21) reported on quality control tests on PVC pipe that had been in use for a number of years. Subsequent to that effort, additional quality control tests of excavated PVC pipes were completed. The pipes tested are summarized in Table 1 and had been in continuous use for between 20 and 49 years. Note that samples #1, 4, and 6 were manufactured under an early commercial standards CS 256 or PS 22-70. The CS 256 and PS 22-70 standards were replaced with ASTM D2241 and the standards are nearly identical. The tests included pipe dimensions, acetone immersion, and pressure tests. The burst pressure test was used for samples that were manufactured to CS-256, PS 22-70, and ASTM D2241 standards. The hydrostatic integrity test was applied to sample #3 which was made to the AWWA C905 standard. Table 2 lists the specifications used for these quality control tests. Figure 1 is a photograph of Sample #3 prior to the hydrostatic integrity test.

Table 1. Description of PVC Pipe Tested at USU

Sample Number	Size (inches)	SDR	Usage	Standard	Year Installed	Year Excavated	Years of Service
1	4	21	Water Main	CS-256	1964	2012	49
2	4	21	Water Main	ASTM D2241	1987	2012	26
3	24	18	Forced Sewer	AWWA C905	1990's	2012	~20
4	2	26	Water Main	CS-256	1980's	2014	~42
5	4	26	Water Main	ASTM D2241	1980's	2014	~38
6	6	26	Water Main	PS 22-70	1980's	2014	~38
7	6	26	Water Main	ASTM D2241	1994	2014	20
8	6	26	Water Main	ASTM D2241	1979	2014	35

Table 2. Quality Control Test Specifications

Test	Test condition	Applicable Standards
Pipe Dimensions	6 specimens at 8 points	AWWA C905 & ASTM D2122
Acetone Immersion	8 samples	ASTM D2152
Burst Pressure	SDR 21, 630 psi in 60 s	CS-256, PS 22-70, ASTM D2241 &

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	SDR 26, 510 psi in 60 s	D1599
Hydrostatic Integrity	SDR 18, 470 psi in 60 s	AWWA C905 & ASTM D1599

Figure 1. Photo of sample #3 prior to structural integrity testing.

The results of the testing is summarized in Table 3. As previously reported, during the 1970's a few manufacturers did have problems with their extrusion equipment and did not always obtain proper gelation as shown by the failures of samples 4 and 6 to pass the acetone test. The failure of sample 4 to pass the Burst Pressure test is attributed to improper gelation. Note that samples 4 and 6 were both manufactured under the early PS 22-70 standard. After passing the burst test, the samples were pressurized until failure. The failure pressure was consistently more than 20% higher than the specified burst test pressure called out in Table 2. Thus, where proper fusion of the PVC was obtained, there are no indications from these quality control tests that there has been any degradation in these PVC pipe specimens

Table 3. Results of Quality Control Tests

Sample	Pipe Dimensions	Acetone Test	Burst or Hydrostatic Integrity Test
1	Pass	Pass	Pass
2	Pass	Pass	Pass
3	Pass	Pass	Pass
4	Pass	Fail	Fail
5	Pass	Pass	Pass
6	Pass	Fail	Pass
7	Pass	Pass	Pass
8	Pass	Pass	Pass

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It is significant to note that this was the second round of testing performed on sample #1. In 1987 Eckstein (22) reported that samples of this pipe was excavated in 1987 after 22 years of use and subjected to chemical extractant tests for water quality, stress regression tests per ASTM D1598 and D2837, acetone immersion testing per ASTM D2152, flattening tests per ASTM D2412, and impact resistance tests per ASTM D2444. All of these quality control tests were passed. The latest round of testing of sample #1 verifies that the ability of the 49 year-old pipe to perform its intended purpose has not changed. The pipe has the same water pressure capacity it had when it was first installed 49 years previously.

DIG-UP TEST RESULT SUMMARY

Accelerated ageing studies all indicate that PVC pressure pipe can be expected to provide reliable service for in excess of 100 years. Accelerated ageing tests provide the best estimates a laboratory can provide for longevity. Validation of PVC expected long term performance with exhumed samples provides additional confidence to the end user. With many installations of PVC pipe reaching 50 years with no indication of loss of capacity, this provides further validation of PVC pipe’s long life.

Examples can be found of PVC pipe failures with very short life spans. When an early PVC failure occurs, it has been the experience of the author that there will be two possible causes. The failure could be due to a defective pipe usually caused by incomplete gelation of the PVC. Quality control tests by manufacturers on each lot of pipe should prevent this occurrence. The primary cause of early PVC pipe failure is improper installation procedures. Regardless of the pipe material chosen, a quality installation procedure will provide enhanced pipe life.

SEWER PIPE STUDIES

Bauer (16) tested PVC sewer pipe exhumed after 15 years of service and in 1990 reported on tests that no measurable degradation of the material occurred in this period. In particular it was reported that there was no embrittlement and no decrease in modulus or pipe stiffness.

Meerman (23) in 2008 conducted inspections of sewer pipe up to 25 years old. A number of pipes were recovered from their service sites and subjected to a range of visual, microscopic and other test to assess their condition. The tests included: visual and microscopic inspections, geometrical analysis and deformations, and surface roughness and degradation. He concluded that the existing PVC sewer pipe systems will operate for at least 100 years.

CONCLUSION AND RECOMMENDATIONS

Our water and sewer underground infrastructure is now in decline after decades of service. The signs of distress surface daily as water mains break, creating floods and sink holes. The loss of service is more than an inconvenience, causing significant social and economic disruptions at ever increasing costs. The downturn of the economy has also given rise to new issues on the affordability of water services when total price tag of regulatory issues and replacement costs are considered. These issues create a more complex environment for utility management, including an increased amount of public awareness and a greater demand for transparency and accountability. In an effort to provide solutions to these new utility business requirements, additional processes and tools are needed as part of the underground pipe infrastructure evaluation and selection process. Many utilities have fallen short in producing appropriate cost and life cycle comparison of pipe performance. When PVC pipes are included in life cycle costing with accurate expected life assumptions, utilities will see significant possible savings.

As previously mentioned, the average age of a failing water main is 47 years. This is unacceptable and unsustainable. Studies on the expected life of PVC pipe from researchers around the world consistently has confirmed a 100+ year benchmark for PVC pipes. These results are based on “dig-up” studies of pipe in use and installed by contractors. All pipe installations, regardless of the pipe material, require a quality installation. Attention to installation will pay dividends in terms of extended life.

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REFERENCES

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1. Water Infrastructure Network, Clean and Safe Water for the 21st Century, April 2002. http://www.win-water.org/reports/ winreport2000.pdf.
2. Dawn of the Replacement Era: Reinvesting in Drinking Water Infrastructure, 2001. (http:// www.win-water.org/reports/infrastructure.pdf.)
3. American Water Works Association, "Buried No Longer: Confronting America's Water Infrastructure Challenge," 2012.
4. Clark, M. C, Carson, J., Thurnau, R. C., Krishnan, R., and Panguluri, S., "Condition assessment modeling for distributions systems using shared frailty analysis," Journal AWWA, July 2010, pp. 81-91.
5. Folkman, S. L., Rice, J., Sorenson, A., and Braithwaite, N., "Survey of Water Main Failures in the United States and Canada," AWWA Journal, American Water Works Association, Oct. 2012, vol. 104, no. 10, pp. 70-79.
6. Anderson, Richard F., Ph.D., Municipal Procurement: Procurement Process Improvements Yield Cost-Effective Public Benefits, U.S. Conference of Mayors, Mayors Water Council, March 2013. (http://www.usmayors.org/publications/ media/2013/0422-waterprocurementWP.pdf.)
7. Kirby, P. C., "PVC Pipe Performance in Water Mains and Sewers," Int. Conference on Underground Plastic Pipe, ASCE, New Orleans, March, 1981.
8. Bjorklund, I. and Janson, L. E., "Swedish experience of the use of thermoplastic pipes for water and sewage transport," International Conference on Underground Plastic Pipe, New Orleans, 1981, pp.385-400.
9. Burn, S. et. al., "Long-term Performance Prediction for PVC Pipes," AWWARF Report 91092F, May 2006.
10. Lancashire, S. J., "In-Service Durability of uPVC Water Mains," Plastics Pipes VI Conference, March, 1985.
11. Alferink, F., Janson, L. E., Holloway, L., "Old PVC-U Water Pressure Pipes: Investigation into Design and Durability," PVC 1996 Conference Proceedings, 42C382 Institute of Materials, Brighton, England, April 1996, pp. 87-96.
12. Hülsmann, T., and Reinhard, E. N., "70 years of experience with PVC Pipes," 13th World Pipe Symposium, Milan, Italy, April 2004.
13. Boersma, A., Breen, J., "Long term performance prediction of existing PVC water distribution systems," 9th International Conference PVC, Brighton, England, April 2005.
14. Breen, J., "Expected Lifetime of Existing Water Distribution Systems – Management Summary," TNO Report MT-RAP-06-18692/mso, published by TNO Sicence and Industry, April 2006.
15. Stahmer, M. W., and Whittle, A. J., "Long Term Performance of PVC Pressure Pipes in a Large Rural Water Supply Scheme," Plastics Pipes XI Conference, Munich, Germany, Sept. 2001.
16. Bauer, D. E., "15 Year Old Polyvinyl Chloride (PVC) Sewer Pipe: A Durability and Performance Review," STP1093 Buried Plastic Pipe Technology, ASTM, 1990, pp.393-401.
17. Whittle, A. J., and Teo, A., "Resistance of PVC-U and PVC-M to cyclic fatigue," Plastics, Rubbers and Composites, vol. 24, 2005, pp. 40-46.
18. Moser, A. P. & Kellogg, K., "Evaluation of Polyvinyl Chloride (PVC) Pipe Performance," AWWA Research Foundation, Project #708, Order #90644, February, 1994.
19. Moser, A. P. and Folkman, S. L., Buried Pipe Design, McGraw-Hill, 3rd Edition, 2008, Chapter 4.
20. Seargeant, D., "PVC Water Distribution Pipe; EPCOR's Continuing Success," Uni-Bell Annual Meeting, Newport Beach, CA, April 2013.
21. Folkman, S, and Barfuss, S., "Validation of PVC Pipe's Long Life Performance," Uni-Bell Annual Meeting, Newport Beach, CA, April 2013.
22. Eckstein, D., "PVC Pressure Pipe Excavation Reveals 22 Years Old and Fit as a Fiddle," Uni-Bell PVC Pipe News, Summer, 1987.
23. Meerman, M, "Lifetime Expectancy of PVC-U pipelines for sewer systems," International Conference Plastics Pipes XIV, Budapest Hungary, September 22-24, 2008.

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