LARGE DIAMETER PVC PIPE – CANADIAN EXPERIENCE

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The use of Polyvinyl-Chloride (PVC) pipe in Canada has been very widespread and successful for pressure pipe applications. Smaller sized (300 mm {12"} and less) PVC pipe has become the dominant material for water utilities providing benefits such as corrosion resistance, hydraulic capacity, ease of installation, and trouble-free performance. For these same reasons, larger sizes of PVC pressure pipe have been used more and more each year with tremendous success. This paper will provide a background into some design and installation issues for the use of larger diameter PVC pressure pipe and provide some Canadian and North American experience with the product.

PVC RESIN

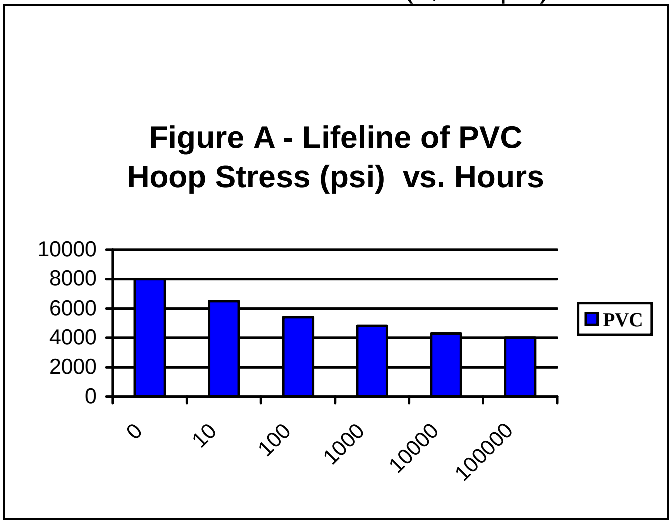
PVC in its raw form is a granular material derived from two common substances – chlorine and ethylene. The chlorine is extracted from sodium chloride (salt) while the ethylene is a natural gas by-product. The two components each represent approximately 50% of the PVC molecule by weight. A similar thermoplastic piping material, polyethylene consists of essentially 100% ethylene and thus is more closely related price-wise to fluctuations of the natural gas market than would be PVC.

Resin is the base material for PVC compounds which are specific mixtures of resin plus additives to allow the granular material to be extruded into pipe or other products. Common additives are waxes, lubricants, colors, heat stabilizers and UV inhibitors. Different PVC pipes for different applications will typically have different specific and proprietary PVC compounds used.

STRENGTH OF MATERIALS

If one were to imagine PVC as a brand new material, never having been used for piping, the first question a designer might ask would concern the strength properties of the material. To respond to this inquiry, the attached bar graph (Figure A) would be helpful.

The maximum tensile strength of PVC is dependent on the duration of the stress being applied. For example, if the stress is to be applied for a few hours, the tensile strength might be as high as 55.2 MPa (8,000 psi), while if the stress is to be applied for 10,000 hours (approx. one year), the strength would be a more moderate value of 31.0 MPa (4,500 psi).



Thus one may ask what would be a suitable maximum tensile strength for long-term pressure pipe applications. It has been determined that the strength of a thermoplastic resin at 100,000 hours can effectively be defined as the long-term strength of the material. This point is defined as the Hydrostatic Design Basis (HDB) of the plastic compound. In this case, for PVC 12454 compound as specified by most pressure pipe standards, the HDB will be 27.6 MPa (4,000 psi).

DIMENSION RATIO

To proceed in learning about PVC pressure pipe, the term ‘Dimension Ratio’ must be defined. Dimension Ratio (DR) is a dimensionless unit that represents physical characteristics of the pipe. It is defined as the ratio of a pipe’s outside diameter to its minimum wall thickness, i.e. DR = OD/t. The terms DR and SDR are interchangeable.

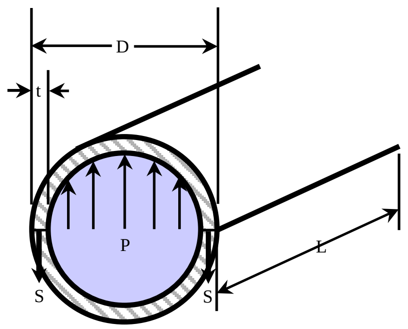
It is important to understand that the lower a DR number will be, the thicker will be the pipe. The DR terminology is very convenient for design analysis as properties such as pressure rating and structural strength are identical for all diameters of the same DR. In other words, one could expect the same pressure rating and structural strength for underground burial with a 150 mm (6”) DR25 and a 900 mm (36”) DR25.

The DR terminology is also commonly used with high-density polyethylene (HDPE) pipe for identifying the various diameter to thickness ratios available.

RELATING HOOP STRESS TO PRESSURE – ISO EQUATION

Using a balance of forces analysis, a relationship between the tensile stress limits of the material and the corresponding internal pressure can be shown (see Figure B). It should also be pointed out that in a pressure cylinder, the stress acting in the circumferential direction is twice the value of that acting in the longitudinal direction. Thus, the circumferential stress (also called Hoop Stress) is used as the critical stress value for a pipeline under internal pressure.

Figure B - Relating Hoop Stress to Pressure



Balance of Forces

Assuming the stress is acting on the centre of the pipe wall, the balance of forces analysis will yield, P (OD – t) = 2 (S)(t), where P = internal pressure, and S = resultant hoop stress on the material. By substituting DR for OD/t, the equation can be rearranged to be P (DR-1) = 2St, or **P = 2S / (DR-1).**

The above equation is defined as the ISO Equation for thermoplastics and is critical for assigning maximum pressure ratings for various DR thicknesses of PVC pipe, based on maximum tensile stress values.

<u>PVC Pressure Pipe Standards</u>

There are 4 main standards in use today in Canada and the United States for PVC pressure pipe. Each is described briefly below:

AWWA C900-07 – for cast iron outside diameter (CIOD) pipe in sizes 100 mm – 300 mm (4" – 12"), used mainly within water distribution systems;

AWWA C905-08 – generally for water transmission applications, available in sizes 350 mm – 1200 mm (14" – 48"), also made mostly as CIOD;

ASTM D 2241-05 – pipe made for agricultural, mechanical or other pressure applications, made to Iron Pipe Size (IPS) OD, available in sizes 38 mm – 600 mm (1.5" – 24")

CSA B137.3-05 – pipe made to either CIOD or IPS-OD, third-party certified, covering sizes 38 mm – 1200 mm (1.5" – 48")

Each of these pipe standards includes specifications for raw material requirements, dimensions and tolerances, required marking and quality control testing. It should also be noted that PVC pipe made to any of the above four standards is also commonly used for sewage forcemains.

PRESSURE RATINGS OF PVC PIPE

In general, the pressure rating of a thermoplastic pipe would be more accurately defined as its Long-Term Pressure Rating. It is intended to be a maximum internal pressure for continuous, steady-state operation of the pipeline over its lifetime.

The pressure ratings assigned to different DR's are derived by using the ISO Equation with a Hydrostatic Design Stress, HDS. This value of HDS is determined by applying a factor of safety (FS) to the HDB of the material.

Specifically for large diameter PVC pipe, the safety factor chosen is 2.0. This value is consistent with safety factors used in other AWWA and ASTM standards for plastic pipe and often exceeds the factor used for other piping materials such as steel or concrete.

Thus, it can easily be determined that after applying a 2.0 FS to the HDB of 27.6 MPa (4,000 psi) for PVC, the HDS value will be 13.8 MPa (2,000 psi).

By using the ISO Equation for all the DR's offered by AWWA C905, the various pressure ratings can be determined, and are shown below:

DR	C905 Pressure Rating	
	(kPa)	(psi)
51	550	80
41	690	100
32.5	860	125
26	1100	160
25	1140	165
21	1380	200
18	1620	235
14	2100	305

It is interesting to note that if any of the above DR's of PVC pipe (in any diameter) were subjected to the full internal pressure of its rating, there would be exactly 13.8 MPa (2,000 psi) of hoop stress being applied to the PVC material. These ratings are consistent with those derived according to the AWWA C900, ASTM D 2241 and CSA B137.3 standards although the DR's may vary slightly.

AWWA C900 Changes

A significant change was made in the 2007 revision of AWWA C900. From its inception in 1975, C900 had always included a SF = 2.5 and a 0.8 m/s (1 ft/s) surge allowance in de-rating the pipe's pressure classes. However, after much discussion at committee levels, it was found that the design philosophy of C900 was overly conservative and that a SF = 2.0 with no built-in surge allowance would be more appropriate. Thus, C900 is now consistent with the other 3 major standards in assigning its pressure ratings or classes.

QUALITY CONTROL PRESSURE TESTING

In order to better appreciate the reserves of strength in PVC pipe, one should be aware of hydro-test requirements of AWWA C905. Specifically, each individual length of pipe must be hydro-tested at the plant to twice its pressure rating. This very thorough test has been a key contributor to the stellar performance track record of PVC pressure pipe. It is highly unlikely for any defective pipe to escape the factory to the marketplace.

In addition to this, pipe certified to CSA B137.3 will be subjected on a daily basis to hydro-testing to 3.2 times the pressure rating. This testing includes an assembled gasketed joint of the pipe to ensure the joint is not a weakness.

Both of the above tests provide physical evidence to the high levels of short-term strength of PVC pressure pipe versus its more conservative long-term pressure ratings.

In addition for CSA, the pipe must be able to withstand a negative pressure test of 75 kPa (-10.8 psi) for a period of 1 hour. Zero leakage is permitted for this testing. This test is an important factor when considering gasket joint PVC pressure pipe for low pressure sewage forcemain applications, where negative pressure transients are more commonly found.

It should also be noted that in some engineering specifications, the term 'Allowable Leakage' is referred to for PVC and other pipes for field pressure testing. This term is often misinterpreted to imply that gasket joints of PVC are always leaking to some degree. This is definitely not the case for properly installed PVC pipe. As evidenced in the CSA and AWWA plant testing, zero leakage is allowed for those tests. A more correct term for the test procedure is 'Make-Up Water Allowance' which would account for any possible minor leakage in the system during pressure testing. Should any make-up water be required after a 1 or 2 hour pressure test and a small pressure drop, it can likely be attributed to minor shifting of elbows when subjected to thrust forces, radial expansion of the PVC pipe, or weeping at system components such as valves, hydrants, service saddles or air relief valve connections. A large or fast pressure drop will indicate a leak in the system which must be located and repaired. More information on specific test procedures for PVC pipe can be obtained from the

AWWA C605 standard, "Underground Installation of PVC Pressure Pipe and Fittings for Water."

To further understand the different levels of strength for PVC pressure pipe compounds, AWWA Design Manual M23 defines a new term, Short-Term Rating (STR) for different DR's of PVC pipe. This rating is used in design procedures when evaluating the strength of a PVC pipeline in withstanding short-term, occasional transient surges in a pipeline, such as those that might occur from rapid valve closure or power failures of pump systems. Without entering a full discussion of this term, it is noteworthy that these STR's permit occasional total pipeline pressures to exceed the long-term rating of the PVC pipeline while maintaining generous factors of safety. The STR's for several DR's of PVC pressure pipe as per AWWA M23 are shown below:

DR	Short-Term Rating (STR)	
	(kPa)	(psi)
51	690	100
41	880	128
32.5	1100	160
25	1450	210
18	2070	300

SURGES PRESSURES IN PVC PIPE

One advantage to the designer in using thermoplastic pipe such as PVC is that the inherent flexibility of the material contributes to lower pressure surge values in the system under transient conditions. PVC has a modulus of elasticity of 2,760 MPa (400,000 psi) which compares very favorably to much higher values for metal pipe. As a result, the surge pressures generated in a PVC pipeline for a 0.8 m/s (1 ft/s) instantaneous velocity change would be as shown below:

DR	0.8 m/s (1 ft/s) Surge	
	(kPa)	(psi)
51	74.5	10.8
41	78.7	11.4
32.5	88.3	12.8
25	101.4	14.7
18	120.0	17.4
14	136.6	19.8

These values compare very favorably with those typically found for metallic or concrete pipe which are in the order of 345 kPa (50 psi) per 0.8 m/s (1 ft/s) velocity change. It can also be seen that as PVC pipe gets thicker (i.e. with a lower DR), the surge pressure generated increases as the pipe becomes slightly more rigid.

It should also be noted that surge pressures can only be very accurately predicted and designed for using transient software. The practice of predicting surge pressures using the actual velocity multiplied by the above table values represents a good guideline and is often referenced in pipeline standards and design manuals.

THRUST RESTRAINT

Wherever an unbalanced force exists in an underground pipeline, regardless of material, the designer must account for restraint of these thrust forces to ensure the pipeline remains intact. The three factors in the magnitude of these thrust forces are size of pipeline, magnitude of internal pressure and geometric nature of the force imbalance.

For PVC pipe, thrust restraint may be achieved in two ways – concrete thrust blocks or mechanical restrainers. Thrust blocks will not be discussed in this paper and the reader is referred to industry or pipe manufacturers' publications for more information.

Mechanical restrainers however are gaining popularity with large diameter PVC pipe. The restrainers are essentially sets of metallic collars that are clamped against the pipe exterior and bolted together. They are designed to dig in when thrust forces occur so that the pipe will not pull apart from adjacent pipes or fittings. There are restrainers designed specifically for PVC pipe which may vary greatly from those used on iron pipe. The PVC restrainers will generally contain a number of serrations on the contact surface that will evenly clasp onto the PVC pipe exterior under thrust pressures without imposing significant point loading on the pipe.

Restrainers for PVC pipe are commercially available in North America from manufacturers such as Ford Meter Box, Ebaa Iron, Clow, Star Pipe Products and JCM Industries. Most of these manufacturers have design software available to assist in selecting the proper model and quantity of pipeline restrainers for specific projects.

In Canada, mechanical restrainers have been used successfully on PVC pressure pipe up to sizes of 1050 mm (42”). Advantages include space saving versus large concrete thrust blocks and faster installation of the pipeline.

ULTRA-VIOLET EXPOSURE

When PVC pipe is exposed to sunlight for prolonged periods, it is possible for some discoloration of the exterior surface to occur due to Ultra-Violet (UV) rays.

What actually occurs is that a chemical change occurs on the surface whereby a very shallow layer of PVC becomes a harder and stiffer plastic. The depth of discoloration is often no deeper than .08 mm (.003”).

Most properties including pressure capacity and structural strength are unaffected by discoloration from UV rays. This fact has been confirmed in various research tests including one for testing of a 350 mm (14”) C905 pipe from Saskatchewan, Canada. This particular pipe was able to pass all physical testing of AWWA C905 and CSA B137.3 after sitting in an outside yard for 15 years in a climate of approximately 2,400 hours of sunshine per year.

FITTINGS

For C905 pipe, there are two main options for fittings. Standardly available cast or ductile iron fittings are most often used since the PVC pipe often carries the same OD as ductile iron pipe. As second option is fabricated PVC fittings. Some advantages of fabricated PVC fittings are excellent corrosion resistance, flexibility to make bends of special angles, and very deep bell-spigot connections for the pipeline. Fabricated PVC fittings are now part of the AWWA C905 standard which contains some minimum quality control standards. Generally the fittings are made from pipe of equal or higher thickness as the DR of pipe being used and may often times be reinforced with fiberglass for added structural strength.

MAJORS USERS IN CANADA FOR C905 PIPE

Below are several of the larger users of large diameter PVC pressure pipe in Canada as well as a few in the United States that were supplied out of Canada.

W. Canada Sewer Utilities – PVC has been the preferred product for large diameter sewage forcemains in major centres of Western Canada such as Victoria, Vancouver and Edmonton for many years. DR41 pipe has been most popular in these larger sizes since most forced sewer pipelines operate at lower pressures. Bare cement lined pipe is not permitted in these utilities for forcemains due to Hydrogen Sulfide corrosion concerns.

W. Canada Water Utilities – Cities such as Edmonton, Calgary, Saskatoon and Winnipeg have long preferred PVC pipe for watermains due to excellent corrosion resistance and performance. Soils in Canada’s three Prairie Provinces have a high sulfide content and have been problematic on buried metallic pipe. PVC has been an excellent solution in all sizes with 1050 mm (42”) representing the largest sized installation to date.

Irrigation Districts – These rural water utilities distribute low pressure water from rivers through a network of piping for local farmers to purchase for irrigation. Many pipe materials have been tried over the years such as concrete, steel, fiberglass and profile PE. PVC has given unmatched performance versus all others due to joint tightness, ease of installation, durability and excellent flow capacity. Preferred dimension ratios are 51, 41 and 32.5 with IPS-OD being most common up to 600 mm (24”) sizes. Also, fabricated PVC fittings are dominant. Strong support in this market made the decision easy to enter production of sizes up to 1200 mm (48”) over the years as buried piping has many advantages over the alternative – irrigation canals.

Province of Ontario – Canada’s most populated province uses C905 DR25 piping as a standard for most water transmission mains. The market continues to grow at the expense of traditionally used concrete cylinder pipe for the larger sizes. Most utilities specify that the pipe supplier do an engineering review of every project design with special attention given to joint restraint design.

Design-Build Projects – PVC has had a successful track record thus far in design-build water transmission lines. Part of this can be attributed to the options of using higher DR’s of pipe in lower pressure zones of a long pipeline thus making the overall piping project more economical. The installation-friendly nature of PVC pipe is also helpful when compared to alternative materials for these projects.

Various US Projects – Since larger sizes of C905 pressure pipe were first made in Canada, several US utilities became aware of the larger pipe being available and specified it for use. Thus, PVC pipe from Canada has been supplied for larger diameter projects dating as far back as 1980 for 500 mm (20”) pipe in Utah. Various other projects up to 1200 mm (48”) have also been successfully installed for water, forcemain or irrigation applications Colorado, Oregon, Arizona, Florida and Louisiana amongst others. This widespread success has led to US pipe manufacturers expanding production sizes up to 1200 mm (48”) in recent years to help meet this growing demand.

PVC PRESSURE PIPE RESEARCH

As PVC pipe usage has grown steadily over the last 30 years in Canada, more and more research has become available to help support its strong performance. Some of these are discussed below:

National Research Council of Canada (NRC) Break Rates – In the early 1990’s, NRC surveyed over 100 water utilities in Canada for break-rate data for different watermain materials in use in their respective water supply systems. PVC scored by far the most favorable break rate at 0.7 breaks per 100 km (62 mi.) of installed pipe on average. The next closest material was ductile iron which failed at a rate of 7.9 times per 100 km. Since this study, many water utilities have made recording of watermain break data an essential part of ongoing evaluation of materials and best practices.

City of Edmonton 27-Year Old Pipe – In an effort to evaluate the predicted life of PVC pressure pipe, the City of Edmonton Water Utility (now known as EPCOR) decided to excavate and test one of their very first installations of PVC water pipe. A section of the 1977 installation was first excavated and tested in 1994, and secondly in 2004 and found to have identical strength properties to that of new pipe. EPCOR continues to be a strong user of PVC pressure pipe and is satisfied that PVC pipe should last for the entire duration of their water system depreciation time period of 88 years.

University of Toronto Vinyl Pipe Testing – Burst testing was conducted on 600 mm (24") PVC DR25 pipe made to AWWA C905 in an effort to verify the short-term burst strength theory used in the standards. The pipe sample with a pressure rating of 1140 kPa (165 psi) was found to burst at a pressure of 3860 kPa (560 psi), or a hoop stress of 46.4 MPa (6,720 psi). The very generous factors of safety in PVC pressure ratings were verified.

Utah State University – This school has long been recognized as one of the more advanced with respect to studies for underground pipelines. Two significant tests have been performed with respect to PVC pipe. The first was subjecting PVC sewer pipe to extreme structural loads and holding their loads for as long as 30 years to observe crack resistance. No cracks were found thus confirming how PVC has the ability to stress relax for constant loads over time. The second test was more directly relevant to pressure pipe design whereby a number of pipe samples were subjected to cyclic pressure testing until failure. This test data enabled researchers to generate a chart to predict the cyclic life for PVC pressure pipe in various conditions. Most notably for watermains was that small fluctuations in pressure which are common in water lines do not inflict noticeable fatigue stresses on a PVC pipeline and thus are not considered a limiting design factor.

Additional Resources

There is a wealth of technical information available today with respect to the design and installation of PVC pressure pipe.

These sources include:

Uni-Bell PVC Pipe Association – Dallas, TX (www.uni-bell.org)

American Water Works Association – Denver, CO (www.awwa.org)

ASTM International – Pennsylvania (www.astm.org)

Canadian Standards Association – Toronto, ON (www.csa.ca)

PVC Pipe Manufacturers (www.ipexinc.com)