How Plastic Pipes Flow Economically, Socially, and Environmentally into a Modern Infrastructure

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Abstract

Plastic pipe materials, they have been around for over 60 years but are still not being used exclusively. They offer huge advantages over their predecessor materials that are corrosion and abrasion prone; two of the largest issues with which the water industry is dealing. The three main types of plastic pipe materials include: polyvinyl chloride, polyethylene, and glass reinforced plastics. Each of the materials offers advantages over the other and where one may be suitable for a situation another may not. Plastic pipes are good for new construction as well as for rehabilitation of older system. They offer a wide range of characteristics that make them good candidates for trenchless methodologies which saves substantial real and social costs. A modern infrastructure is one that is concerned with all three tiers of sustainability: environment, economics, and social. Plastic pipes give the water industry the ability to take the water infrastructure in the direction of sustainability, which it is far from now.

Overview of Current American Water Infrastructure with Solutions for the Future

The condition of the United States critical infrastructure is in catastrophic disrepair. So why is this important? "One of the key signs that we are in the early stages of an economic collapse and that we are heading towards another Great Depression is America's crumbling infrastructure" (The Economic Collapse, 2010). There are many systems which make up the critical infrastructure of the United States; these include but are not limited to the transportation system such as roadways and airports, waterways and harbors, and electric generation plants. However, the most important infrastructure system is that of water delivery and wastewater handling (PVC Pipe: Superior Performance in Critical Systems). Water infrastructure includes potable water, stormwater, and wastewater. It is not adequate having one of these systems functional and the others non-functional. All of these systems are critical to the safety of the public and are necessary to allow the public to live the quality of life to which Americans are accustomed (Najafi, Salem, Bhattachar, Salman, & Patil, 2008).

It will take huge financial contributions as well as creative solutions to close the gap between the current spending and the future need for water infrastructure (Agency, 2002). Between 1950 and 2000, although there was only a 159% growth in population there was a 207% growth in water usage; that equates to a 20% per capita raise in water usage (Engineers, 2009). Having adequate water systems is the first line of defense against water-borne diseases, preventing sickness and reducing healthcare costs (PVC Pipe: Superior Performance in Critical Systems). However, human health is not the only reason for safe water. Having clean water is responsible for close to $400 billion in revenue from water based recreation, coastal tourism and commercial fishing (PVC Pipe: Superior Performance in Critical Systems).

When it comes to creating a water infrastructure there are several pipe materials that may be used; these materials include concrete, metal, or plastic. Plastic pipe does not face the same challenges as these others when it comes to durability and therefore is becoming more often the material of choice (Najafi et al, 2008).

Simultaneous Degradation of Current Water Infrastructure and Considerations for Re-Structure

The pipes which make up the water infrastructure in the United States were installed in three main time periods throughout history and they all coincided with substantial population growth; these time periods included the 1800s, 1900-1945, and post 1945 (Folkman, 2012). While back 100 years ago the extent of water pipes were made up of clay, brick, and sometimes wood nowadays there is a whole list of available materials used for making water pipes; these materials include high density polyethylene (HDPE), polyvinyl chloride (PVC), ductile iron, fiberglass reinforced, steel, concrete, polymer concrete, and vitrified clay (Bueno, 2010).

The issue that is occurring now is that even though these pipes were installed in three different time periods they are all expected to start failing at the same time. The difference in material and their expected useful life along with some other factors have all of these pipes in need of replacement within the next few decades (Folkman, 2012). There are pros and cons to each type of material and each type must be evaluated for the specific site at which it will be used. In the sections below some of the main issues that have to be considered when choosing a material are considered. It is important to understand these issues to see why the use of plastic pipe in a modern infrastructure is often the best choice.

Conditions Which Cause Pipes to Fail

There are two categories into which modes of failure can be divided: the first category is material deterioration due to corrosion, abrasion and debris that is stuck in the structure, and the second includes internal loads such as operational pressure and externals loads due to soil overburden (Kleiner & Rajani, 2001). All of these modes of failure affect each pipe material differently. Although this paper's focus is plastic pipes it is important to understand all of these modes of failure to see why the use of plastic pipe is advantageous.

The first category of failure modes that needs to be looked at is that of material deterioration. Material deterioration is normally caused by corrosion, abrasion, debris, or a combination thereof (Kleiner & Rajani, 2001).

Corrosion, which is the deterioration of metal is not limited to metal pipes, it can also affect the metal reinforcement in a concrete pipes. Simply put, corrosion is the "process of metals returning to their native states of oxides or salts" which begins to occur when water with a low pH value, acids, bases, salts, oils, and chemicals which act as an electrolyte interacts with the metal components (Salem & Najafi, 2008). Once corrosion begins it is a self-sustaining process creating pits in the metal weakening the pipe and can cause failure (Najafi & Gokhale, 2005). Corrosion is a huge issue with direct costs only totaling $36 billion annually. This does not consider any indirect cost of having broken water pipes which would raise the total cost due to corrosion substantially (PVC Pipe: Superior Performance in Critical Systems).

Abrasion is the next item looked at in this first category of failure modes. Abrasion is the wearing a way of material such as the pipe wall due to materials flowing through the pipe (Salem & Najafi, 2008). This mode of deterioration can ultimately cause failure. It can also lead to accelerated corrosion which in turn leads to the ultimate failure of the pipe (Najafi et al, 2008).

The combination of abrasion and corrosion is most prevalent in steel pipes. Water with a very high pH as well as water with a very low pH can help accelerate the affects of abrasion (Salem & Najafi, 2008).

The final form of deterioration that is looked at is debris. This seems like a simple item to deal with and to take care of but that is not always the case. The main issues that are caused by having debris stuck in the pipes is that it causes the system not to be able to run at full capacity as well as increases the chance of abrasion to occur (Salem & Najafi, 2008).

The second category of failure modes that needs to be looked at is that of loads that are applied to the pipe. This includes both internal as well as external loads. Figure 1 shows a general picture of a pipe and the many loads which it may incur.

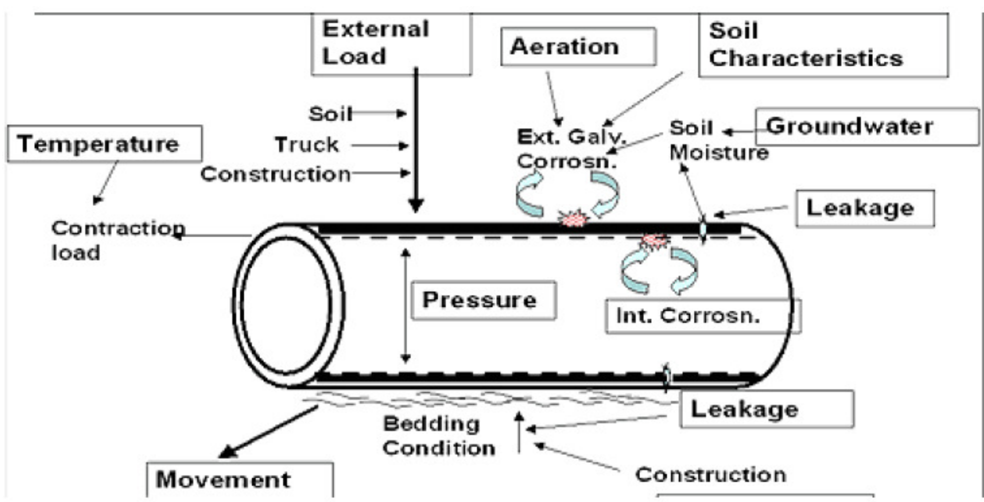

Figure 1: Modes of failure that can be incurred by a pipe. (Salem & Najafi, 2008)

Internal loads are mainly due to pressures that the pipe is placed under during operation (Najafi & Gokhale, 2005). Internal loads can occur in both pressure and gravity pipes. If blockage occurs this will increase the operation pressures the pipe feels and has more likely of a chance of failure.

External loads on the other hand cover a much broader range of issues. They can include everything from soil overburden to seismic activity; basically anything that puts a pressure on the outside of a pipe is considered an external load (Najafi & Gokhale, 2005). Refer back to Figure 1 to see other forms of external loads.

Using Trenchless Technology as the Solution to Water Loss and Main Breaks

Another issue that is of concern with today's water infrastructure is that of water loss. Water loss occurs due to joints that have corroded as well as with water main breaks. The later of the two is an easier fix, at least when it comes to water loss prevention because it can be located and repaired. On the other hand, when joints leak it is not that no one is aware of it but rather that it has become accepted that this occurs. The American Society of Civil Engineers has estimated that the leaky joints in water pipes waste 2.6 trillion gallons of potable water every year which is equivalent to 17% of all water that is pumped throughout the United States (Solving the Corrosion Epidemic in Water Infrastructure with PVC Pipe) with some cities such as Washington D.C. which lose as much as 50% of their potable water that is pumped through their pipes (Stewart, 2005). There are too many joints to go through and repair when other issues such as the 700 (PVC Pipe: Superior Performance in Critical Systems) to 850 daily water main breaks have to be attended to (Economic Impact of the PVC Pipe Industry).

The best remedy for leaky pipes is rehabilitation of part or all of the system and the best methods for this are through trenchless technology. Trenchless technology is non-intrusive and normally is 25% - 30% cheaper and causes less disruption (Stewart, 2005). The constraints of each project will dictate which method is applicable.

Plastic Pipe: What is it?

Improvements in material science have given water infrastructure a new material that is resistant to many of the issues typically dealt with when using the materials that were available in the past. This material is plastic. It has the ability to provide an equivalent service life as that of concrete or metal but in a greater range of environments (Najafi et al, 2008). A huge advantage that plastic pipes have is that they are non-corrosive and have excellent abrasion resistance (2010 Pipe Materials Guide, 2010). Since 1977 the pipe market has grown substantially, nearly doubling. A huge portion of that growth is that of plastic pipes, accounting for nearly 80% of that growth (PVC Pipe: Superior Performance in Critical Systems).

Plastic pipes were introduced into the United States in the late 1950s and since then it has become the preferred material for water infrastructure (Najafi, 2010). The main reasons for the move towards plastic pipe is the fact that it is lighter to transport and therefore cheaper to transport, easier to handle, easier to install, easier to maintain, and all with a service life of over 100 years (Stewart, 2005). There are three main types of plastic pipe, these include polyvinyl chloride also known as PVC, polyethylene also known as PE, and finally glass reinforced plastic also known as GRP or fiberglass pipe (Najafi & Gokhale, 2005). These three plastic pipe materials can be split into two different categories which are thermoplastics and thermoset plastics; thermoplastics are made up of PVC and PE while thermoset pipes are made out of GRP (Najafi, 2010). The main difference between thermoplastics and thermoset pipes is that thermoplastics can be heated, formed and reshaped time after time while thermoset pipes are processed with heat and chemicals and therefore once formed cannot be reshaped (Najafi & Gokhale, 2005).

Table 1 below gives a quick overview of the three main types of plastic which are used in the water infrastructure of the United States. Following the table will be sections dedicated to each of the plastic types allowing for a more detailed look at each of them.

Table 1: Types of plastic (2010 Pipe Materials Guide, 2010).

Type of Plastic		Best Suited For	Trenchless Applications	Diameters	Design Life
Thermoplastics	Polyvinyl Chloride (PVC)	• Buried water • Buried reclaimed water • Buried force mains • Buried sanitary sewer • Buried storm sewer	• Segmental sliplining • Directional drilling • Close-fit pipe lining • Pipe bursting	• 1 ½ " to 60" for gravity • 1 ½ " to 48" for pressure	Excess of 100 years
Thermoplastics	High Density Polyethylene (HDPE)	Underground water applications	• Horizontal directional drilling • Pipe bursting • Sliplining • Plow and plant	• ½"to 65" for solid wall • 2" to 60" for corrugated • 2" to 120" for spiral-profile wall • ½" to 2" for crosslinked PE pipe	50 – 100 years
Thermoset	Fiberglass Reinforced Pipe (GRP)	• Potable water • Force main sewer • Gravity sewer	• Sliplining • Microtunneling • Directional drilling • Pipe jacking • Pipe bursting • Tunnel lining • Casings	18 in -158 in	Excess of 50 years

Polyvinyl Chloride (PVC)

PVC was discovered by accident in the 19th century; however, it was decades later when its application in water infrastructure started (Najafi & Gokhale, 2005). The first PVC pipe was installed in Germany during WWII and is still in use today (Najafi & Gokhale, 2005). After the war ended PVC was brought to the United States and has been used ever since (Najafi & Gokhale, 2005). Although the plastic pipe industry has grown as a whole PVC pipes makes up a majority of that growth (PVC Pipe: Superior Performance in Critical Systems).

Currently PVC pipes make up 48% of the infrastructure for water, wastewater, and stormwater systems; accounting for over two million miles of pipe that is currently in service (Economic Impact of the PVC Pipe Industry). It is used by over 54,000 drinking water systems, 10,000 water treatment facilities, 15,000 sewer and water contracting firms, and over 70 independent distributors of water and wastewater products; all in all accounting for over $5.5 billion in sales back in 2008 (Economic Impact of the PVC Pipe Industry). Currently PVC accounts for approximately 78% of all new pipes that are being laid in North America (PVC Pipe: Safe and Beneficial to Public Health).

PVC has many advantages compared to the materials normally used in the past. When a survey was conducted by the American Water Works Association Research Foundation PVC came in with a satisfaction rating of 4.1 out of 5 which was higher than any other material surveyed (PVC Pipe: Superior Performance in Critical Systems). The reasons for this high satisfaction with PVC are many and will be discussed further in this section.

One of the main issues when dealing with water infrastructure that has been discussed previously in the paper is that of water leaks and main failures. Due to the leak free and non corrosive gasket joints PVC pipes reduce water loss and provides water loss rates of less than three percent which are easily achievable and does not occur at the pipe joints (PVC Pipe: Best Choice for the Environment; PVC Pipe: Superior Performance in Critical Systems). Having leak free joints also helps prevent contamination in the water system (PVC Pipe: Superior Performance in Critical Systems). Not only does daily water loss reduce but also the amount of water that is lost due to main breaks. According to one survey every 100 km or 62 miles of water line laid PVC only had 0.7 breaks per year while the previous conventional materials had much higher rates, for example cast iron had 35.9 breaks per year and ductile iron had 9.5 breaks per year (PVC Pipe: Superior Performance in Critical Systems). Another survey had relatively similar but slightly higher failure rates of 2.7 breaks per 100 miles per year (Walker, 2007). The survey also found that North American PVC outperformed PVC produced in other countries and that these failure rates increase gradually with age on PVC pipe as opposed to metal pipe where the failure rates accelerate with age (Walker, 2007).

PVC has a long useful life. Although results vary, all say that when designed and installed properly PVC has a life expectancy of greater than 100 years (2010 Pipe Materials Guide, 2010; PVC Pipe: Superior Performance in Critical Systems; Walker, 2007). Extensive quality control helps with the life expectancy of the product. Each pipe is stamped with information referencing it to its production code where quality control records are maintained for a minimum of two years (PVC Pipe: High Quality and Performance Standards). It is one of the safest and most tested materials that is used in North America (PVC Pipe: Safe and Beneficial to Public Health). It can even be used in applications where its previous metal counterpart was harmful. PVC unlike metal has a high compatibility with sea water, where once animals were getting sick and dying with the use of metal pipes they are now living healthy lives with the use of PVC pipes (Mason, 2006).

Some of the most convincing reasons PVC is a preferred material for water infrastructure have briefly been discussed in the general plastics section; these include its resistance to both internal and external corrosion, erosion, abrasion, and its smooth interior surface. It is also resistant to the majority of chemicals that are found in wastewater and leaves no trace of taste, odor, or contamination in the water that it transports (PVC Pipe: Superior Performance in Critical Systems).

Another benefit of PVC is its strength and flexibility. PVC can handle external loads of 75,000km/m^3 or what is equivalent to around 40m of ground cover and it has the flexibility that allows it to bend and flex without breaking (PVC Pipe: Superior Performance in Critical Systems). The strength and flexibility of PVC pipe allows it to be able to handle frost heave, frost load, some seismic activities, and any other event that would cause pipes to crack and joints to fail (Najafi & Gokhale, 2005).

When one begins to look at the future and how PVC plays a role in it there are many issues that need to be taken into account. Some of these issues include the ease of using trenchless methods for both new pipes and for the rehabilitation of old. Finally, the environmental impact of PVC on the environment and the cost savings of it must be looked at as well.

Construction of new or rehabilitation of old water infrastructure although necessary can come with some hefty price tags. However, not all of the cost is “real”, a lot of the costs that are dealt with on a project are social costs (PVC Pipe: The Right Choice for Trenchless Projects). Trenchless technologies or “no-dig” procedures help to greatly reduce both the real and social costs of a project (PVC Pipe: The Right Choice for Trenchless Projects). PVC pipe is widely used in trenchless construction of water infrastructure for many of the same reasons it is used in open cut methods. Below in Table 2 is a list of trenchless methods which PVC is applicable.

Table 2: Trenchless technologies that are applicable for the use of PVC pipe (Najafi et al, 2008; PVC Pipe: The Right Choice for Trenchless Projects).

<table>
<tr><th colspan="2">Method</th><th>Application</th></tr>
<tr><td colspan="2">Horizontal Directional Drilling (HDD)</td><td>New construction for pressure and gravity piping systems</td></tr>
<tr><td rowspan="2">Sliplining</td><td>Segmental</td><td>Renewal of gravity piping systems</td></tr>
<tr><td>Continuous</td><td>Renewal of pressure piping systems</td></tr>
<tr><td colspan="2">Close-Fit Structural Liner</td><td>Renewal of pressure and gravity piping systems</td></tr>
<tr><td colspan="2">Pipe Bursting</td><td>Replacement of pressure and gravity piping systems</td></tr>
</table>

PVC is actually a very environmentally friendly product, again especially when compared to its older counterparts. It is actually one of the most sustainable products in the world. It is produced with chlorine, which is derived from salt and domestically produced natural gas (PVC Pipe: Best Choice for the Environment). It takes fewer pounds of materials in order to produce a linear foot of PVC then it takes to produce a linear foot of metal or concrete (PVC Pipe: Superior Performance in Critical Systems) and with the fact that it is a thermoplastic material it can be completely recycled and reused (2010 Pipe Materials Guide, 2010). There are no smoke stacks producing greenhouse gasses at PVC producing facilities, comparing it to concrete again, the cement which is used in concrete is the world's third largest producer of greenhouse gasses (PVC Pipe: Best Choice for the Environment). Lastly, PVC is highly efficient. Almost 100% of the PVC compound is used to create pipe. When compared to concrete it takes four times less energy to produce the PVC and when compared to iron pipe it uses half of that energy (PVC Pipe: Best Choice for the Environment). So when comparing to the common previously used pipe materials PVC has a much smaller carbon footprint and ecological rucksack all of which is very important to be able to move forward into a modern infrastructure.

Finally, the last tier of sustainability is the economic side of things. Savings from using the current PVC pipes that are in place is estimated to be $270 million a year and if the entire sanitary sewer system was converted to PVC pipes the savings would increase to $800 million a year with an additional $4.1 billion savings every year in wasted electricity that is used to pump water through leaky and broken pipes (Economic Impact of the PVC Pipe Industry). Another place that PVC can save money is one that is not as obvious, however substantial, with the ultra-smooth interior surface of the PVC pumping costs will decrease as will the cleaning and maintenance costs due to the fact that there will be less build-up in the pipe system (PVC Pipe: Superior Performance in Critical Systems).

Polyethylene (PE)

As with many inventions it was invented for a use other then what it is used for now. In 1933 PE was invented in the United Kingdom and became commercialized in 1939, however, the use was for insulating telephone and coaxial cables and was not until the 1950s when it came to the United States and was mainly used in the gas industry (Najafi & Gokhale, 2005). Although PE is not the leading pipe resin it has big opportunities in the water infrastructure due to its flexibility, sturdiness, and joint integrity (Stewart, 2005). There are two main reasons for the success of PEs growth within many municipalities. The first of these is the ability of it to be used in multiple trenchless technologies and going along with that the second reason is the lack of other materials whose joints are able to be fused together (Najafi & Gokhale, 2005).

PE is classified into three groups based on its density and crystallinity. The American Society for Testing and Materials (ASTM) has classified these into Type 1 or low-density polyethylene, Type 2 or medium-density polyethylene, and Type 3 or high-density polyethylene (Najafi & Gokhale, 2005). It also comes in solid wall and profile wall options; the solid wall HDPE is suitable for use in gravity as well as pressure water systems while profile wall HDPE is only suitable for gravity water systems (Najafi & Gokhale, 2005). For the use of PE pipes in a water infrastructure the high-density polyethylene (HDPE) is the most commonly used pipe, however, medium-density polyethylene (MDPE) pipe can be used but it is rare. For this reason this section will focus on HDPE.

Refer back to Figure 1 for basic information on HDPE. It may have a higher initial cost but is less expensive overall throughout its entire useful life, mainly due to the limited maintenance that it requires (Stewart, 2005). That useful life that is mentioned should range between 50 and 100 years or more (2010 Pipe Materials Guide, 2010). HDPE is corrosion resistant internally and externally (Najafi & Gokhale, 2005) and offers the best abrasion resistance of all plastic pipes (DROSSBACH GmbH & Co., 2011). It is also highly flexible resisting shatter-type as well as rapid crack-propagation failures and acts well in cold temperatures having a high resistance to impact fractures (Najafi & Gokhale, 2005).

Looking into the future and the needs of a modern infrastructure HDPE should have a bright future. HDPE has a low carbon footprint, a long service life, low maintenance, and is completely recyclable since it is a thermoplastic material (2010 Pipe Materials Guide, 2010). This makes it the preferred material for trenchless installation (2010 Pipe Materials Guide, 2010) as does the fused joints that create a continuous jointless pipe (Najafi & Gokhale, 2005). However, because the profile wall HDPE has a lower compressive strength it does not work in all trenchless technologies that are applicable to HDPE pipe (Najafi & Gokhale, 2005). Table 3 summarizes the common trenchless technologies that are applicable to HDPE. To try to help solve the strength limitations with HDPE there is a cooperative effort to build a production system to create continuous steel-reinforced HDPE pipe that would be used in drainage applications (Stewart, 2005).

Table 3: Trenchless technologies that are applicable to HDPE pipe (2010 Pipe Materials Guide, 2010; Najafi et al, 2008).

Method		Application
Horizontal Directional Drilling (HDD)		New construction for pressure and gravity piping systems
Sliplining	Segmental	Renewal of gravity piping systems
	Continuous	Renewal of pressure piping systems
Close-Fit Structural Liner		Renewal of pressure and gravity piping systems
Pipe Bursting		Replacement of pressure and gravity piping systems

Glass Reinforced Plastic (GRP)

Glass reinforced plastic pipe is also commonly known as fiberglass pipe and was invented in the United States in the 1950s as an alternative to the more corrosive prone materials previously used (Najafi & Gokhale, 2005). It is currently the least used of the three main plastic materials which are discussed in this paper and the only one that is a thermoset plastic; however, it is growing quickly in popularity for use in the larger diameter pipes in both water and sewer applications (Najafi & Gokhale, 2005).

Similar to the other plastic pipe materials GRP is highly corrosion resistant inside and out (2010 Pipe Materials Guide, 2010). It has a smooth interior which helps prevent debris build up inside the pipe (Najafi et al, 2008). It is lightweight even when compared to other plastic materials making transportation and installation easy, (Najafi & Gokhale, 2005) and has a high strength to weight ratio (Stewart, 2005). All of these material characteristics make GRP have a long service life, one in excess of 50 years (2010 Pipe Materials Guide, 2010).

As said before the future of GRP pipe in a modern infrastructure looks promising. It lends itself to trenchless methods which are the way of the future (Stewart, 2005). Table 4 shows the main trenchless technologies that for which GRP pipe is suitable.

Table 4: Trenchless technologies that are applicable to GRP pipe (2010 Pipe Materials Guide, 2010).

Method		Application
Horizontal Directional Drilling (HDD)		New construction for pressure and gravity piping systems
Pipe Jacking		New construction for pressure and gravity piping systems
Sliplining	Segmental	Renewal of gravity piping systems
	Continuous	Renewal of pressure piping systems
Pipe Bursting		Replacement of pressure and gravity piping systems

Conclusion

Considering the American Society of Civil Engineers rates the water infrastructure as a D- is an ominous warning that the future of life as Americans know it is in jeopardy (ASCE, 2009). Plastic pipe has been a huge step forward towards sustainability in the improvement of the water infrastructure. It is said that the invention of PVC is “one of the top twenty engineering advancements in the last 125 years” (Solving the Corrosion Epidemic in Water Infrastructure with PVC Pipe). It is imperative that advantage is taken of this improvement to remedy this situation before it’s too late. Demand for plastic pipe is expected to continue to grow at a rate of 5.6% per year (US Plastics Pipe Growth, 2008). Although each type of plastic pipe discussed has strengths that the other ones do not necessarily have they all are highly corrosion resistant, flexible, and lightweight making all of the different materials more durable, workable, and cost effective then their previously used counterparts. By selecting materials with these characteristics and long useful lives the constant water infrastructure repair and replacement crisis that is now being faced will be an issue of the past.

References

2010 Pipe Materials Guide. (2010). *Trenchless Technology*.

Agency, U. S. (2002, September). *The Clean Water and Drinking Water Infrastructure Gap Analysis.* Retrieved from epa.gov: http://www.epa.gov/ogwdw/gapreport.pdf

ASCE. (n.d.). *Report Card for America's Infrastructure* . Retrieved from Infrastructure Report Card: http://www.infrastructurereportcard.org/

Bueno, S. M. (2010). What Lies Underground? . *Trenchless Technology Special Supplement - 2010 Pipe Materials Guide*, pp. 8-11.

DROSSBACH GmbH & Co. (2011, June). The Advantages of Corrugated Pipe Systems. Germany.

Economic Impact of the PVC Pipe Industry. (n.d.). *PVC: Pipe Association Issue Brief*. Retrieved from Pipe Association.

Engineers, A. S. (2009). *Report Card for America's Infrastructure.*

Folkman, S. (2012). *Water Main Break Rates In the USA and Canada: A Comprehensive Study.* Logan.

Kleiner, Y., & Rajani, B. (2001). Comprehenssive Review of Structural Deterioration of Water Mains: Statistical Models. *Urban Water*, 131-150.

Mason, K. (2006, Winter). When Water Quality Matters PVC Delivers. *PVC Pipe News*, p. 8.

Najafi, M. (2010). *Trenchless Technology Piping: Installation and Inspection.* Alexandria: Mc Graw Hill.

Najafi, M., & Gokhale, S. (2005). *Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal* . New York: Mc Graw Hill.

Najafi, M., Salem, S., Bhattachar, D., Salman, B., & Patil, R. (2008). *An Asset Management Approach for Drainage Infrastructure and Culverts.* Madison.

PVC Pipe: Best Choice for the Environment. (n.d.). *PVC Pipe Association Issue Brief*.

PVC Pipe: High Quality and Performance Standards. (n.d.). *PVC Pipe Association Issue Brief*.

PVC Pipe: Safe and Beneficial to Public Health. (n.d.). *PVC Pipe Association Issue Brief*.

PVC Pipe: Superior Performance in Critical Systems. (n.d.). *PVC: When Performance Counts*, pp. 1-4.

(n.d.). *PVC Pipe: The Right Choice for Trenchless Projects.*

Salem, O., & Najafi, M. (2008). *Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures.*

Solving the Corrosion Epidemic in Water Infrastructure with PVC Pipe. (n.d.). *PVC: Pipe Association Issue Brief*.

Stewart, R. (2005, January). Plastic Pipe: Corrosion resistance, ease of installation stimulate demand for plastic pipe. *Plastics Engineering*, pp. 14-21.

The Economic Collapse. (2010, April 21). Retrieved from America's Crumbling Infrastructure: http://theeconomiccollapseblog.com/archives/americas-crumbling-infrastructure

US Plastics Pipe Growth. (2008, October 10).

Walker, B. (2007, Summer). AWWARF Looks at PVC Pipes' Long-Term Performance. *PVC Pipe News*, pp. 3-4.