Field Performance of Coatings and Linings for Welded Steel Pipe in the Water Industry

Sylvia C. Hall, P.E.[1]

Abstract

Linings and coatings have been used for more than 150 years to protect steel water pipe from corrosion. As demonstrated in common field and environmental conditions, some coating and lining systems are better than others at extending the service life of water transmission pipelines with virtually no maintenance. Two systems have been used for over 100 years with a proven history. Some systems, for various reasons, are no longer used. Other systems have been introduced in the last 25 years and have yet to prove long service life in actual installed conditions.

The historical performance of lining and coating systems for welded steel water transmission pipelines in the United States under a variety of field and environmental conditions are presented and discussed. These systems are included in internationally-used waterworks standards.

This paper presents the results and recommends best practices for the selection of lining and coating systems for welded steel pipe in the water industry.

Introduction

Coatings and linings are used on steel pipe in the water industry primarily to protect steel from the corrosive action of soils, groundwater, and the transported water. Coatings are materials applied to the exterior of the pipe to mitigate corrosion from the surrounding soil and groundwater. Linings are materials applied to the interior of the pipe to mitigate corrosion due to the transported water.

Coatings and linings can be grouped into three categories: 1) passivating, such as portland cement mortar, 2) bonded, dielectric materials, such as coal tar enamel, epoxies,

[1] Director, Engineering Development Center, Corporate Research & Engineering, Ameron International Corporation, 8627 Atlantic Ave, South Gate, CA 90280, PH (323) 564-6626; FAX (323) 563-8208; e-mail: Sylvia_Hall@ameron.com

and polyurethanes, and 3) unbonded materials, such as polyethylene encasement used on cast and ductile iron pipe.

One passivating material (portland cement mortar) and nine bonded dielectric materials (coal tar enamel, liquid and fusion-bonded epoxies, tape, extruded and fused polyolefins, polyurethanes, polyamide, and fusion-bonded polyethylene) are included in the American Water Works Association C200 series of standards and are discussed in this paper.

History and Quantity Used

A summary of the history of the various coating and lining systems for steel pipe in the C200 series of AWWA standards is given in Table 1.

Table 1
History of Coatings and Linings on Buried Steel Water Pipelines

Coating or Lining System	Exterior Coating	Interior Lining	First Use	AWWA Standard	First Edition of AWWA Standard
Portland Cement Mortar	X	X	Before 1836	C104 C205 C602	1939 1941 1955
Coal Tar Enamel	X	X	Mid 1930's	7A.4 & 7A.5 C203 C203	1940 1951 Coating 1973 Lining
Liquid Epoxy	X	X	1950's	C210	1978
Fusion-Bonded Epoxy	X	X	1960 (gas line)	C213	1979
Tape	X		~1960	C214	1983
Extruded Polyolefin	X		1956	C215	1988
Polyurethane	X	X	1980's	C222	1999
Polyamide	X	X	1970	C224	2001
Fused Polyolefin	X		1988	C225	2003
Fusion-Bonded Polyethylene	X		1960's	C229	2008

Estimated percentages of water transmission steel pipe coated and lined with the various coating systems during the past several decades are given in Table 2.

Portland cement mortar. The history and performance of mortar coatings and linings on water pipelines have been extensive and excellent for more than 100 years (Bardakjian 1995, Bardakjian and Hausmann 2007, AWWA C205 2007). One of the first mortar-lined and coated steel pipelines was installed in the City of St. John, New Brunswick, Canada in 1855. A section of the pipeline, which transported relatively aggressive potable water, was removed from service due to line relocation in 1963 after 108 years of service and the interior and exterior was found to be free of corrosion (Bardakjian 1995, Bardakjian and Hausmann 2007). Cement-mortar-lined-and-coated steel pipe was first used in the United States in the late 1800s. Some of the first pipelines were in service for almost a century by the time the first national standard was written (AWWA C205 2007).

Table 2
Estimated Percentage of U. S. Water Transmission Steel Pipe
Coated and Lined with Various Systems During the Past Several Decades

Coating or Lining System	% Pipe with Exterior Coating	% Pipe with Interior Lining
Portland Cement Mortar	45 – 55	>95
Coal Tar Enamel	5 – 10	<1
Liquid Epoxy	<1	<3
Fusion Bonded Epoxy	<1	<1
Tape	35 – 45	NA
Extruded Polyolefin	5 – 10	NA
Polyurethane	<5	<2
Polyamide	<1	<1
Fused Polyolefin	<1	NA
Fusion-Bonded Polyethylene	<1	NA

Besides being used on steel pipe, the need for a better lining to combat tuberculation at pinholes of hot-dip bituminous-lined cast-iron pipe led to the first use of portland cement mortar linings in cast-iron pipe in 1922 (AWWA C104 2008).

Portland cement mortar is the predominant lining system for steel, cast-iron, and ductile-iron water pipelines. Portland cement mortar or portland cement concrete is always used as the lining system in concrete pressure pipe. As given in Table 2, use of mortar lining in water transmission steel pipelines for at least the past 50 years is estimated at greater than 95%. The remaining small percentage of steel water pipelines that do not use portland cement lining systems are typically penstocks and above-ground pipelines.

Coal tar enamel. The history and performance of coal tar enamel coatings on water pipelines have also been extensive and excellent since the mid-1930s (AWWA C203 2008). The primary reason for its excellent performance is due to the roughly 1/8-inch thickness of the coating that had been typically applied when compared to the much thinner coatings and linings used in the other dielectric coatings (see Thickness section). In the past decade or two, coal tar enamel has been used less often due to health and environmental concerns. Coal tar is a suspected carcinogen and the volatile organic compound (VOC) content and odor of the material emitted during application in particular have caused stringent permitting requirements for its use in populated areas. These issues have forced some companies to refrain from applying coal tar enamel to pipe.

<u>Liquid and fusion-bonded epoxies, tape, extruded and fused polyolefins, polyurethanes, polyamide, and fusion-bonded polyethylene</u>. From 1941 until 1978, portland cement mortar and coal tar enamel were the only two materials listed in AWWA standards. During the next 11 years from 1978 to 1988, four additional coating systems (liquid and fusion bonded epoxies, tape, and extruded polyolefin) and two lining systems (liquid and fusion bonded epoxies) were added. In the 1960's, the single layer fusion bonded epoxy (FBE) was introduced as an external coating in the oil and gas industry and is now the most commonly used pipeline coating for oil and gas transmission pipelines in North America (Thomas 2010). Due to U. S. Department of Transportation regulations, all buried and dielectrically-coated oil and gas pipelines are required, for all practical purposes, to be cathodically protected to protect any exposed steel at pinholes, flaws, and cracks in the coating (US CFR 2009).

During the last 12 years, four coating systems (polyurethanes, polyamides, fused polyolefins, and fusion-bonded polyethylene) and two lining systems (polyurethanes and polyamides) were added to the AWWA standards. These bonded, dielectric coating and lining systems have been only used sparingly on buried water pipelines and, as such, do not have the extensive performance history of portland cement mortar and coal tar enamel.

Thickness of Coatings and Linings

The minimum or the range of coating thicknesses of the ten coating and linings systems in the C200 series of AWWA standards is given in Table 3.

Table 3
Thickness of Coating and Lining Systems

Coating or Lining System	AWWA Standard	Exterior Coating Thickness	Interior Lining Thickness
Cement Mortar	C205	0.75" minimum	0.50" minimum
Coal Tar Enamel	C203	3/32" ± 1/32" plus outer wrap	3/32" ± 1/32"
Liquid Epoxy	C210	0.016" minimum	0.016" minimum
Fusion Bonded Epoxy	C213	0.012" – 0.015"	0.012" – 0.015"
Tape	C214	0.046"-0.055" (≤54" ID); 0.073"-0.088"(>54" ID)	Not used
Extruded Polyolefin	C215	Min. 0.030" (2" ID) to Min. 0.068" (144" ID)	Not used
Polyurethane	C222	0.025" minimum	0.020" minimum
Polyamide	C224	0.009" – 0.024/0.040"	0.009" – 0.040"
Fused Polyolefin	C225	0.048"-0.054" (≤54" ID); 0.072"-0.081" (>54" ID)	Not used
Fusion-Bonded Polyethylene	C229	Min. 0.063" (≤10" ID) to Min. 0.090" (>30" ID)	Not used

Figure 1 shows a comparison of the thickness of several of the coating and lining systems. The minimum thickness of the portland cement mortar coating and lining systems are ¾ in. and ½ in., respectively, which is substantially thicker than any of the dielectric coating and lining systems. The minimum thickness of the nine dielectric coating systems, except for the coal tar enamel system, range from 0.009 to 0.090 in.

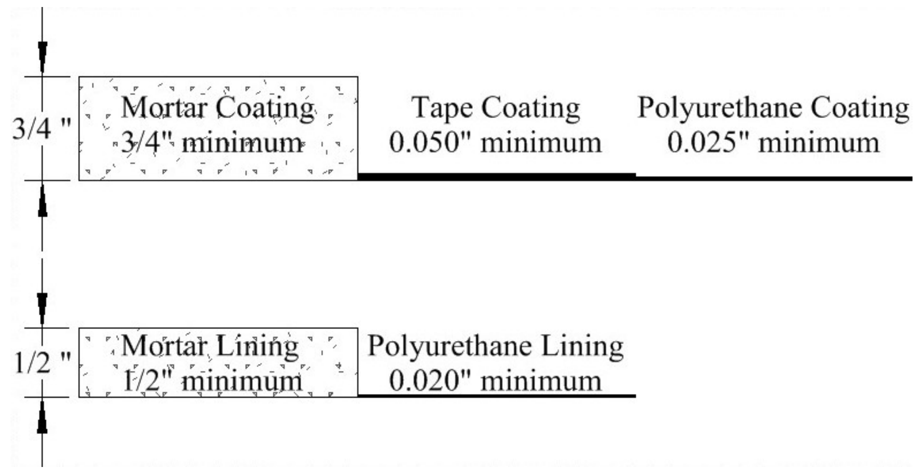

Figure 1. Comparison of thicknesses of several coating and lining systems.

Due to their thinness, dielectric coatings can be detrimentally affected by abrasion and damage during storage, shipping, installation, and backfilling. Select backfill to prevent damage to the dielectric coatings must be used. Depending on the reliability of installation required, dielectric coatings may be specified to be overcoated with a minimum ¾-inch thick portland cement mortar coating as provided for in AWWA C205 to act as a rock or armor shield to protect the dielectric coating from damage.

Steel Surface Preparation Requirements

The minimum steel surface preparation requirements for the ten coating and linings systems in the C200 series of AWWA standards are given in Table 4. Application of mortar coatings and lining requires minimal, if any, surface preparation of the steel. In contrast, the dielectric coatings all require a minimum commercial blast with a specific surface profile depth and most require that the metal temperature be greater than 5^{o}F above the dew point before blasting.

Estimated Cost of Coating and Lining Systems

The estimated material and application costs of the most commonly used coating and linings systems in the C200 series of AWWA standards are given in Table 5. The least expensive systems are the portland cement mortar coating and lining systems. They are roughly half the cost of the other systems given. This is due to the lower material costs of sand and portland cement, the negligible steel surface preparation required, and the ability to coat and line in a wider range of weather conditions.

Table 4
Steel Surface Preparation Requirements

Coating or Lining System	AWWA Standard	Blast Cleaning Requirement	Surface Profile Depth, mil	Metal Temperature above Dew Point/Surface Appearance
Portland Cement Mortar	C205	Not Applicable	Not Applicable	Not Applicable
Coal Tar Enamel	C203	Commercial	1.5-3.5	>5°F
Liquid Epoxy	C210	Near White	Ask manufacturer	>5°F
Fusion Bonded Epoxy	C213	Near White	1.5-4.0	No rust bloom
Tape	C214	Commercial	1-3	>5°F
Extruded Polyolefin	C215	Commercial	1.5-4	>5°F
Polyurethane	C222	Near White	2-4	>5°F
Polyamide	C224	Near White	1.5-4.0	No corrosion
Fused Polyolefin	C225	Commercial	1.5-3	>5°F
Fusion Bonded PE	C229	Near White	1.5-5	No rust bloom

Table 5
Estimated Material and Application Costs of the
More Common Coating and Lining Systems

Coating or Lining System	AWWA Standard	Estimated Cost, $/ft^2	
		Shop Applied	Field-Applied
Portland Cement Mortar Coating	C205	0.75 to 1.20	--
Coal Tar Enamel Coating	C203	No current info	--
Tape Wrap Coating (0.080" thick)	C214	1.35 to 1.50	--
Tape with Mortar Overcoat	C214/C205	2.25 to 2.45	--
Extruded Polyolefin Coating	C215	1.35 to 1.75	--
Polyurethane Coating (0.025" thick)	C222	2.00 to 3.75	~3 to 4
Portland Cement Mortar Lining	C205	**0.50 to 0.75**	**~3 to7**
Polyurethane Lining (0.020" thick) **Maintenance Cost**	C222	**2.75 to 3.95** **--**	**~5 to 8** **~1 to 4**[1]

[1] From Helsel and Wissmar 2008.

Methods of Corrosion Protection

Coatings and linings protect steel from corrosion by two different methods, 1) passivation and 2) isolation of the electrolyte from the steel (barrier).

Portland cement mortar. Portland cement mortar coatings and linings protect steel from corrosion by passivation. Portland cement consists of calcium oxide and small quantities of potassium and sodium ions that convert to calcium, potassium, and sodium hydroxides when water is added to the cement and sand mix during pipe manufacture.

This hydration produces a high pH environment greater than 12.5. At these levels, the steel passivates and does not corrode. The passivation effect of portland cement has been investigated for at least 100 hundred years (Rosa et al 1913). Mortar coatings and linings are made using one part ASTM C150 portland cement to not more than three parts ASTM C33 fine aggregate in accordance with AWWA C205. Water and oxygen diffusion through the mortar does not reduce passivation of the steel.

Coal tar enamel, liquid and fusion-bonded epoxies, tape, extruded and fused polyolefins, polyurethanes, polyamides, and fusion-bonded polyethylene. These coatings and linings protect steel from corrosion by isolating the electrolyte (soil and water) from the metal. They act as a barrier to the corrosive soil and water. They are considered bonded, dielectric coatings and linings. Water and oxygen diffusion through these dielectric coatings and linings is detrimental to the protection of the steel surface.

Cathodic protection (CP) – CP is a corrosion control method that is used to protect the steel exposed to the soil or water at flaws, pinholes, or breaks in the barrier coating. It supplies an electric current which counteracts the currents associated with corrosion. It is usually used in conjunction with bonded, dielectric coatings. Due to U. S. Department of Transportation regulations, all dielectrically-coated oil and gas pipelines are required, for all practical purposes, to be cathodically protected to protect any exposed steel at pinholes, flaws, and cracks in the coating from corrosion (US CFR 2009). CP of mortar-coated steel pipe is rarely required (NACE SP0100 2008).

Comparison of Physical and Performance Characteristics of Coating Systems

Various physical and performance characteristics of the coating systems in the C200 series of AWWA standards are given in Table 6. In general, dielectric coatings are easily damaged during transportation, installation, and backfilling while mortar coatings are more durable. Often, mortar coatings are placed over dielectric coatings as a protective armorcoat which also contributes to pipe stiffness. Due to the susceptibility to damage, dielectrically-coated steel pipe should be cathodically protected to protect the steel at the location of damaged coating from the corrosive environment and stray currents.

Water absorption of mortar coating is an important performance characteristic as it relates to chloride ion penetration. Mortar coatings are typically produced with a water content ranging from 7% to 9% based on the total cement and sand weight. This results in absorption values not exceeding 10% and typically range from 8% to 9%. These low absorption values reduce the amount of chloride ions (in corrosive soils and ground waters) that can penetrate the mortar and depassivate the steel. Water absorption, though, also ensures passivation of steel and reduces the diffusion of air and, therefore, oxygen through the mortar coating.

Water and oxygen permeability of dielectric coatings is also an important performance property. Dielectric coatings must have low water and oxygen permeability to prevent penetration of the corrosive water and oxygen needed for corrosion to occur.

Fusion bonded and liquid epoxies, as a general class of coatings, tend to be brittle so they need to be reviewed carefully to determine if they are appropriate for project requirements and specified appropriately to reduce damage during shipping, installation, and backfilling. Fusion bonded epoxies require large expenditures of energy to heat the steel pipe to typical temperatures of 400 to 500°F required for fusion of the epoxy powder. Liquid epoxies have handling problems immediately after application since it takes many hours to become tack free and hard enough to place on a berm. Coal tar enamels have very low water vapor transmission rates.

Table 6
Comparison of Typical Physical and Performance Characteristics of Coatings on Buried Steel Pipelines

Characteristic	Mortar Coating (AWWAC205)	Dielectric Coating (AWWA C203, C210, C213, C214, C215, C222, C224, C225, C229)
Corrosion Control	Excellent	Good to Very Good
Method of Corrosion Control	Passivation	Barrier – Isolation
Water Absorption	Enhances Passivation	Detrimental
Experience	>160 years	75 yr Coal Tar Enamel >30 yrs Tape >10 yrs Polyurethane
Design Life -Durability	>50 to 100 yrs	15 to 30 years
Physical Damage During Delivery/ Installation	Easily Repaired in Field	Specialized Equipment & Material and Skilled Labor Required
Maintenance	Virtually None	CP System
Cathodic Protection (CP)	Not Required, Rarely Needed	Usually Recommended
Stray Current Discharge	Prolonged Exposure without Corrosion	Steel Corrodes Immediately – 20 lbs/Amp/year
Thickness	0.75 inch Minimum	1/16"-1/8" Coal tar enamel Min. 0.009"- 0.09" Others
Cracking or Pinholes	Passivation	Steel Corrodes or CP Needed
Pipe Stiffness	Contributes greatly	No Contribution
Soil Stresses	Not Affected	May Cause Disbondment or Wrinkling of Coating

Comparison of Physical and Performance Characteristics of Lining Systems

Various physical and performance characteristics of the linings systems in the C200 series of AWWA standards are given in Table 7. As noted in Table 1, portland cement mortar linings have been used since 1836 (AWWA C602). In addition, as shown in

Table 2, more than 95% of linings used in operating steel water pipe are portland cement mortar linings. In contrast, the history and experience are much less, and service life is not well established for most dielectric linings on large diameter pipe used in the water industry.

Table 7
Comparison of Typical Physical and Performance Characteristics of Linings on Buried Steel Pipelines

Characteristic	Mortar Lining (AWWA C205)	Dielectric Lining (AWWA C203, C210, C213, C222, C224)
Corrosion Control	Very Good to Excellent	Variable
Method of Control	Passivation Negligible oxygen diffusion	Barrier – Isolation
Water Absorption	Enhances Passivation	Detrimental
Experience	>175 years	Varies by Material, See Table 1
Design Life - Durability	>50 to 100 yrs	20 to 30 yrs
Physical Damage During Delivery/ Installation	Easily Repaired in Field	Specialized Equipment & Material
Maintenance	Virtually None	Inspection Every 5 to 7 years Recommended
Thickness	0.50 inch minimum	1/16”-1/8” Coal tar enamel Min. 0.009” - 0.020” Others
Cracking or Pinholes	Passivation & Autogenous Healing	Steel Corrodes
Pipe Stiffness	Contributes Significantly	No Contribution
Flow Velocity	Up to 12 ft/sec	Varies; Up to 20 ft/sec
Empty Buried Pipeline	Maintain Humidity	Not Affected
Seismically Active Areas	Excellent	Excellent
Water Flow, Flow Friction (Surface Smoothness)	High Hazen-Williams C-Factor – 140 to 150	High Hazen-Williams C-Factor – 140 to 150

Water absorption. The vast majority of fresh water does not harm portland cement mortar linings. Water actually promotes further hydration and strength development of mortar. In most waters, mortar linings allow for autogenous healing of cracks due to a chemical reaction between the bicarbonate ions in the water and the calcium and hydroxide ions in cement. In addition, water within the microscopic pores in the mortar inhibits the diffusion of air (oxygen) to the steel surface that is required for corrosion, allowing mortar lining to continue to protect steel even if all excess alkalinity is leached from the lining.

In contrast, water absorption is very detrimental to dielectric coatings and can cause disbondment of the coating resulting in steel corrosion. The thinness of the dielectric coating also potentially allows for rapid oxygen diffusion to the steel surface resulting in higher corrosion rates.

Maintenance. It is reported that for fresh or potable water immersion the estimated service life of liquid epoxy coating systems ranges from 8 to 17 years before first maintenance re-coating (Helsel et al 2008). The dry film thickness (DFT) of the epoxy systems listed ranged from 6 to 40 mils with a minimum near white metal blast required. It is also reported that the estimated service life of 100% solids 20-mil thick polyurethane coating systems range from 14 to 16 years before first maintenance re-coating (Helsel et al 2008). Portland cement mortar linings require virtually no maintenance.

Flow friction. Hazen-Williams coefficients range from 134 to 150 for centrifugated concrete pressure pipe, 140 to 156.5 for cast concrete pressure pipe, and 144 to 153 for cast concrete tunnels ranging from 12 inches to 216 inches in diameter (Swanson and Reed 1963). These ranges result from tests conducted on 72 different sections of pipelines or tunnels at various locations, ages, flow rates, diameters, and lengths. These results indicate that for pipe with smooth interior linings in good condition, which includes mortar linings (AWWA M11 2004), the average Hazen-William coefficient (C) can be approximated using equation (1):

$$C = 140 + 0.17d \qquad (1)$$

Where d = inner diameter, inches.

Polyurethane linings were recently tested using a 225 ft long 48-inch diameter steel pipe section (Barfuss 2007). The measured Hazen-Williams coefficient ranged from 148.83 to 149.38 at flow rates from 2.2 fps to 16.77 fps. Utilizing equation (1), the expected Hazen-Williams coefficient for this 48-inch diameter pipeline is 148.2. This is essentially the same as the 2007 experimentally-determined value. This comparison verifies that the flow coefficients and equations shown in the AWWA M11 manual should be used for all welded steel pipe with reasonably smooth interior linings, such as the mortar and dielectric linings discussed in this paper.

A USBR memorandum (1975) states "Selection of formula and coefficient of friction should be based on type of system and type of water carried rather than on type of pipe. The same coefficient of friction should be used irrespective of whether the inside surface of the pipe is steel formed monolithic pipe, steel formed precast pipe, mortar lined centrifugally spun, etc."

Seismically active areas. Limited field performance history of dielectric linings in steel water pipelines is available but it is reasonable to expect that they should perform well as long as the steel has not yielded. Mortar linings can sustain 0.1% strain before visible cracking occurs, while steel yields at 0.2% strain. Mortar lining cracks can autogenously heal if the steel cylinder remains intact after a seismic event. They have survived severe quakes, including the Northridge Earthquake, and have an excellent performance record in seismically active areas. In general, either mortar linings or dielectric linings can be used in such service.

Summary

1. Portland cement mortar coatings and linings have been used on steel water pipelines for more than 150 years.
2. Service histories of dielectric coatings and linings vary widely.
3. Coal tar enamel coatings have been used on steel water pipelines since the mid-1930s. In the past several decades, usage has declined due to its suspected carcinogenic nature, odor, and VOC content.
4. Portland cement mortar is the predominant lining system for steel, cast-iron, and ductile-iron water pipelines. Portland cement mortar or concrete is always used as the lining system in concrete pressure pipelines.
5. Dielectric linings have limited performance histories. Any such application should anticipate regular inspection and maintenance.
6. Portland cement mortar coatings and linings are thick, durable, easily repaired, require essentially no steel surface preparation, can be applied in almost all weather conditions, and passivate steel to protect steel from corrosion. They contribute greatly to pipe stiffness in contrast to dielectric coatings and linings.
7. Portland cement mortar coatings and linings benefit from exposure to and penetration of water from the surrounding environment. Dielectric coatings and linings must be designed to be impermeable to liquid water and water vapor.
8. Dielectric linings and portland cement mortar linings are smooth resulting in similar Hazen-Williams coefficients (C-factor) ranging from 140 to 155.
9. Portland cement mortar coatings and linings are considerably less expensive than dielectric coatings and linings, require less maintenance, and are easier to repair.
10. In seismically active areas, dielectric linings are expected to perform well. Portland cement linings have survived severe earthquakes and have an excellent performance record in these conditions.

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