ELECTRIC POWER RESEARCH INSTITUTE

Guidelines for the Evaluation of Cracks in Cement Linings and Coatings

2013 TECHNICAL REPORT

Guidelines for the Evaluation of Cracks in Cement Linings and Coatings

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EPRI Project Manager
D. Munson

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue
Palo Alto, CA 94304-1338
USA

PO Box 10412
Palo Alto, CA 94303-0813
USA

800.313.3774
650.855.2121

askepri@epri.com

www.epri.com

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Becht Engineering Company

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

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The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Becht Engineering Company
5224 Woodside Executive Court
Aiken SC 29803

Principal Investigator
L. Scribner

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Product Description

This report provides guidelines for the evaluation of cracks in cement linings and coatings. Such cracking is a common occurrence, most often caused by shrinkage as water dries from the paste. However, cracks can also result from other events such as pipe deflection due to applied loads or mechanical damage resulting from nearby construction or excavation activities. Normally, corrosion of the pipe underneath small cracks in cement linings and coatings is not a cause for concern because the alkaline environment that exists in the crack creates a very benign corrosion environment. However, larger cracks can be a concern, and there are circumstances when even small cracks can be a concern for the corrosion resistance of the underlying pipe.

Background

Cement mortar is often used to line the inside of metal pipe, especially for lines carrying raw or minimally treated water. Additionally, it is often used to coat the exterior of metal pipe, especially buried carbon steel pipe. Such linings and coatings function to provide a corrosion resistant barrier to help protect the pipe against either the water-side and/or soil-side environment. Exterior cement coatings with embedded steel reinforcing wires or reinforcing bars can also increase the capacity of the pipe to resist soil, heavy surface, and bending loads. Additionally, buried pipe is sometimes encased in concrete when it is used as a backfill material.

Nuclear power plants are performing inspections of their buried and underground piping to comply with industry commitments made in the Nuclear Strategic Issues Advisory Committee (NSIAC) "Underground Piping and Tanks Integrity Initiative." Cement linings and coatings can make inspection of the pipe difficult unless the lining or coating is removed – which is costly and often unnecessary and may even be harmful. Industry experience has demonstrated that intact cement linings and coatings provide sufficient protection such that inspection of the pipe is not needed. However, no consensus guidelines exist as to when inspection of the pipe underneath a crack is warranted.

Objective

To provide guidelines to plant owners for evaluation of cracks in cement linings and coatings

Approach

The project team performed a literature review and technical evaluation of industry standards and available test data to develop the guidelines contained in this report.

Results and Findings

Guidelines are presented that provide crack sizes (width openings) for both cement linings and coatings where corrosion of the underlying pipe is not considered to be a concern. For mortar linings, the key variables include pH and thickness of the mortar, fluid flow velocity, chlorides in the process water, and the Langelier Saturation Index of the process water. For exterior cement coatings, the key variables include pH and thickness of the mortar, chlorides in the soil, and the Langelier Saturation Index of the ground water.

Applications, Value, and Use

The guidelines were developed for evaluation of cracks in cement linings and coatings found in piping systems in commercial nuclear power plants. The guidelines may also be useful for evaluation of similar cracks in commercial electric power generation plants, chemical plants, and process and wastewater plants.

Keywords

Cement lining
Cement coating
Buried piping
Underground piping
Concrete cracking
Mortar lining
Encased pipe

Abstract

Cement mortar is often used to line the inside of metal pipe, especially for lines carrying raw or minimally treated water. Additionally, it is often used to coat the exterior of metal pipe, especially buried carbon steel pipe. Such linings and coatings function to provide a corrosion resistant barrier to help protect the pipe against either the water-side and/or soil-side environment. Exterior cement coatings with embedded steel reinforcing wires or reinforcing bars can also increase the capacity of the pipe to resist soil, heavy surface, and bending loads. Additionally, buried pipe is sometimes encased in concrete when it is used as a backfill material.

Cracking in cement linings and coatings is a common occurrence, most often caused by shrinkage as water dries from the paste. However, cracks can also result from other events such as pipe deflection due to applied loads or mechanical damage resulting from nearby construction or excavation activities.

Normally, corrosion of the pipe underneath small cracks in cement linings and coatings is not a cause for concern. The alkaline environment that exists in the crack creates a very benign corrosion environment. However, larger cracks can be a concern, and there are circumstances when even small cracks can be a concern for the corrosion resistance of the underlying pipe.

Guidelines are presented that provide crack sizes (width openings) for both cement linings and coatings where corrosion of the underlying pipe is not considered to be a concern. For mortar linings, the key variables include pH and thickness of the mortar, fluid flow velocity, chlorides, and the Langelier Saturation Index of the process water. For exterior cement coatings, the key variables include pH and thickness of the mortar, chlorides of the soil, and the Langelier Saturation Index of the ground water.

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Section 1: Introduction

Pipelines made of cast iron, ductile iron and carbon steel all undergo corrosion on the interior surface when in contact with typical cooling waters. This corrosion results in the formation of rust products (including tuberculation) that reduces the pipe inner diameter, increases pressure drop, and reduces the water carrying capacity of the pipe. In addition, the corrosion results in rust-colored water and, finally, the corrosion can reduce the pipe wall thickness sufficiently to cause both leakage and even rupture of the pipe.

Cement Mortar Linings (CML) can prevent almost all of the corrosion damage that is caused by water in contact with the pipe because the alkaline mortar has a pH that makes the cement-metal interface alkaline enough to passivate steel (iron) and stop corrosion. Because the interior surface of the CML is relatively smooth, it also helps maintain the hydraulic capacity of the system. The cement mortar linings for steel pipe typically range from 1/4 inch to 1/2 inch in thickness and can be even thicker depending on the specifications used for manufacture.

CML steel pipe is often externally coated with cement mortar for increased external corrosion resistance, strength, and increased weight to counteract the buoyancy from empty lines. This external coating is typically 3/4 inch minimum thickness regardless of pipe diameter and is reinforced with steel wire or mesh. On the external surface, small cracks in the cement coating should more easily heal than they would in the flowing water service inside the pipe since the water on the exterior is stagnant. An important factor in predicting external corrosion is that in most soils, the corrosion rate of steel decreases with time. This is largely because of the fact that corrosion products, unless removed, tend to protect the metal.[1]

Cathodic protection of the outside of the pipe is certainly possible even with a cement mortar coating but, since the steel reinforcement in the external coating may not be electrically continuous with the pipe, damage to the external mortar-cement could occur as stray current leaves the metal reinforcement on its way to the pipe surface. Cathodic protection of the internal, CML surface of the pipe is also possible but is generally only done on large diameter lines containing seawater.

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[1] AWWA Manual M11, 4th Edition, page 147.

1.1 Causes of Crack Formation

Cracks in the CML or in cement coatings form either during manufacture of the pipe from the shrinkage stresses during concrete curing or from mechanical stress from either dynamic flexure or static deflection loads. The shrinkage cracks that form during manufacture of the pipe are discussed by AWWA C 205 and generally allow for cracks to be much wider than those that form from mechanical stresses. When the mechanical stresses are static, the cracks can be wider than cracks that are continuously kept active by dynamic flexure. For underground piping, static stresses and shrinkage stresses are the predominate reasons for cracks in the CML. Cement cracking and degradation by chemical attack by sulfates, chlorides and MIC are also possible.

1.2 Self-Repair of Cracks

Cracks on the inside of new mortar lined steel pipe have the ability to self-repair by using their "reserve alkalinity" (the hydrated lime) to precipitate calcium carbonate limestone starting at the base of the crack and filling the crack with limestone all the way to the surface.[2]

$$CaO + H_2O \rightarrow Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Quick Lime   Hydrated Lime   Limestone

Older mortar lined steel pipe has less reserve alkalinity because some of the alkalinity will have been lost over time as the mortar continues to react with water and the dissolved and gaseous species of CO_2 and SO_2 in the water – water hardness. As can be expected, the initial thickness of the mortar lining is an important variable. Thus, to predict the lifetime of the older internally cracking mortar linings, the amount of reserve alkalinity left in the lining and the lining thickness are very important variables. When this reserve alkalinity can be measured, a more accurate prediction of remaining life can be made. When the reserve alkalinity of the mortar is not measurable, the life prediction is less accurate.

In contact with service water, the pores in the CML are permeated with both the service water and any gasses that are present. If the calcium ions in the pore water are below some equilibrium level, the calcium contained in the cement matrix will dissolve to reach equilibrium with the pore water and the cement. It is the difference in concentration of calcium ions in the pore water and in the service water that is the driving potential for calcium leaching from the cement matrix pore water into the service water. The dissolution of calcium from the cement paste into the pore water is almost instantaneous whereas the diffusion of calcium ions from the pore water into the service water is a slower process that takes significant time – measured in years. The dissolution interface between the calcium rich and calcium lean mortar often results in an easily visible boundary.

[2] CaO is often referenced in literature to be in the cement although it reacts very quickly with water to form $Ca(OH)_2$. The terms are interchangeable bearing in mind that that one is hydrated and the other is the anhydrous form of the same compound.

In non-aggressive water, a study in the UK estimated that the average calcium depletion depth of 0.1 inch for uncoated centrifugally applied CML takes 45 years.[3]

Service waters have varying levels of dissolved salts and these are present as ions. Soft waters have low concentrations of ions (low carbonate and bicarbonate) and are aggressive to the calcium hydroxide in the hydrated cement. Soft water will also dissolve the calcium silicate hydrates that form the majority of the cured cement. The calcium silica hydrates are slowly hydrolyzed into silica gels. Silica gels have little strength and the result is a soft surface. This leaching is also a function of residence time.

The carbonate and bicarbonate equilibrium in the service water is one of the significant factors in the dissolution of the cement matrix. The calcium hydroxide that is released when the calcium silicates are dissolved then reacts with any carbon dioxide present to form calcium carbonate – limestone. This carbonate reaction lowers the pH of the solution and reduces the corrosion protection to the pipe. This "carbonation reaction" reduces the inhibitory effect of the alkalinity on the pipe.

If the water in the cement pores is already saturated with calcium carbonate, the carbonation reaction will try to exceed the calcium carbonate concentration. This attempt to exceed the calcium concentration in the pore water will force the precipitation of calcium carbonate onto the lining to regain equilibrium. This is true for water of high alkalinity and hardness while waters with low alkalinity and hardness will continue to degrade the cement. The calcium comes into the pore water as a hydroxide and without sufficient carbon dioxide and carbonate to produce a saturated carbonate solution in the pore water, the water will continue to dissolve the calcium hydroxide out of the lining.

When corrosion of the pipe starts, the "free carbon dioxide" in the water will be removed (as carbonate) and the local pH will rise. If enough corrosion occurs, the pH will raise high enough to force calcium carbonate precipitation which forms a protective film over the corrosion area on the pipe wall.

Free carbon dioxide is seldom found in recirculated water systems since the pH is almost always alkaline. It is more often found in once through water systems using soft, slightly acidic water.

1.3 Corrosion Under the Cement Lining

The cement used for lining of pipe is generally type I or type II Portland cement; sulfate resistant type V cement is often selected for seawater environments. Other types of cement are allowed and may have better chemical resistance to unique waters. During the formation of the cement mortar, the cement is mixed with sand and water to form a paste and the various oxides in the cement react to form

[3] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, page 13.

primarily calcium hydroxide (lime) and calcium silica hydrates. Potable water is used to make the mortar and is limited to 250 ppm chlorides[4], but is generally much lower than this.

Various additives can be added to the mortar mix which can reduce the amount of water needed to place the mortar in the pipe. Low cement to water ratios cement mortars have improved density and resist permeation from water.

The reaction of lime with water during hydration generates a high pH environment that inhibits corrosion of the iron or steel pipe. The prevention of corrosion to iron is because the CaO in the alkaline mortar reacts with the water to form a protective $Ca(OH)_2$ film on the steel. The potential of iron in contact with $Ca(OH)_2$ is around -150 to -200 mV with respect to a saturated copper sulfate half-cell and has a pH of about 13.[5] This electrochemical potential is in the passive range for iron and steel and corrosion does not occur. The alkaline layer of the mortar shielding the metal from water is permeable to ions like chloride, the electrochemical potential for passivity is changed and the potential of the iron moves lower into the range of possible corrosion as the chloride concentration rises. The cement mortar has a pH of at least 11 (often 12 or higher) and at this pH, the corrosion of steel is so low that it can be considered to be zero. If free carbonic acid were present in the water, the cement could be carbonated and the pH would slowly drop to as low as 9. Corrosion of steel could start at this pH. However, the free carbon dioxide levels in common recirculated water systems is low and as the pH goes up, the amount of free carbon dioxide goes down. The carbon dioxide also acts to form low permeability $CaCO_3$ scale inhibiting diffusion of damaging species from the water and air.

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[4] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Chapter 1, page 5.

[5] Malic, A.U. et al, Reinforced Cement concrete Pipelines for Desalinated Water Transmission - A Critical - Review and Some Failure Analysis, First Gulf Water Conference, Dubai, October, 1992, page 816.

Section 2: Effects of Service Environment on Cracks

2.1 Chlorides, Sulfates and Oxygen

2.1.1 Chlorides

Table 2-1 suggests that cracks less than 0.015 inch wide can be healed as a function of cement pore water pH and chloride concentration. The effect of increasing chloride levels is to require that the cement be more alkaline. For the cement to be more alkaline, it needs to have residual calcium hydroxide [$Ca(OH)_2$] that has not reacted with carbonate or bicarbonate to form the less alkaline calcium carbonate (limestone) precipitate.

Data from Benedict allowed for the development of a formula for the relationship of the chloride concentration and pH at the metal/CML interface. This relationship attempts to define the conditions for the break-down of the passivity of steel based upon the chloride concentration.[6]

Table 2-1
Autogenous Healing Requirements

Minimum Cement Pore Water pH vs. Chlorides for autogenous healing of cracks less than 0.015 inch[7]	
pH	Max Chlorides in Water, ppm
11.6	70
12.5	700
13.2	8900

[6] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Chapter 7, page 116.

[7] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Chapter 1, page 5.

The following formula was developed from this data from Benedict:

$$pH = 0.7602 \times \log[Cl^{-}] + 10.242$$

The chloride concentration is expressed in ppm. Using this formula, the pH of the cement pore water at the base of the crack can be as low as 10.7 if the chloride ion concentration does not exceed 3.8 ppm. The pH of the steel surface in contact with the cement needs to be 12 or higher to maintain passivity and prevent corrosion with 250 ppm chlorides at the metal/CML juncture. Interestingly, the common recommended limit for chlorides in drinking water is 250 ppm.[8]

CML pipe is used to convey seawater where the chlorides are typically 19,000 ppm. At this high chloride level the corrosion is controlled by increasing the thickness of the lining and limiting crack widths. This helps in controlling the diffusion of oxygen and chlorides to the surface of the metal.

The Pourbaix diagram for iron-chloride-water shows that when the concentration of chlorides increases, the pH of the water inside a crack becomes critical – see Figure 2-1. Pitting of iron and steel can occur if the pH does not increase as the chloride concentration rises. As the concentration of chlorides increases, the pH must also increase to keep the potential in a range where the iron metal stays in the passive, protected range. CML linings are quite alkaline when new with a pH in the range of 12.5. Carbonation of the mortar as it reacts with carbon dioxide over time reduces the pH of the mortar to around 10 and sometimes even lower. As discussed in Section 1.2, it is this normal reaction between calcium oxide and hydroxide with carbon dioxide and bicarbonate that is responsible for autogenous healing of cracks but it does detract from the resistance of the steel under the mortar to corrosion based on the decreasing pH.

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[8] EPA Secondary Drinking Water Regulations: Guidance for Nuisance Chemicals, http://water.epa.gov/drink/contaminants/secondarystandards.cfm

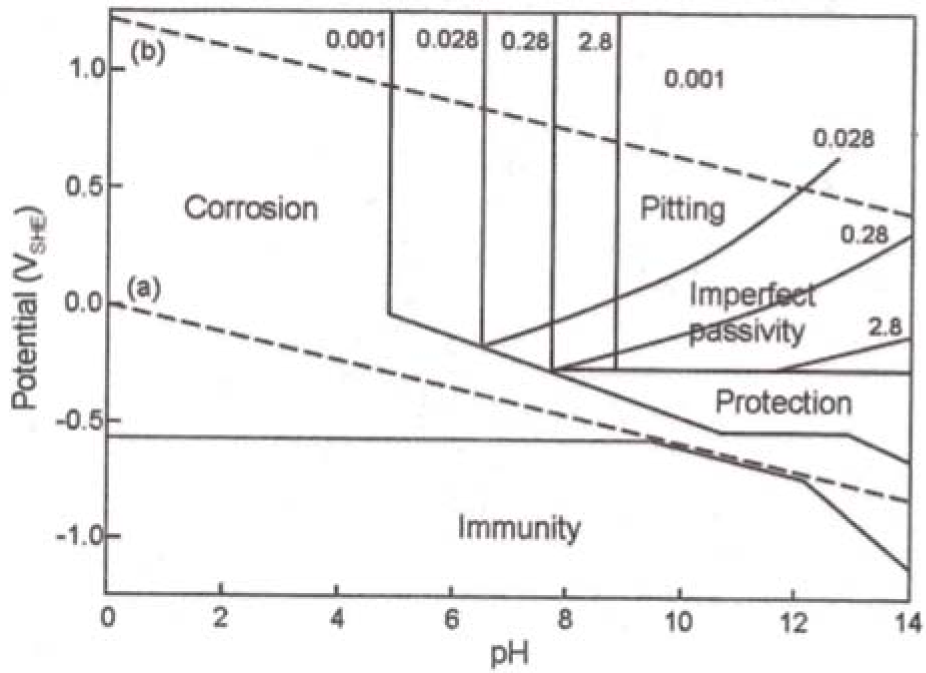

Figure 2-1
Pourbaix diagram for iron in water containing chlorides (mol/l) at 25°C.

This diagram is modeled on the element iron and applies to carbon steel, cast iron, and ductile iron equally. For reference, 1000 ppm chloride ion is equal to 0.028 molar. To prevent corrosion, the pH needs to increase as the concentration of chlorides rise.[9]

In addition to providing a high pH at the cement to pipe interface, the porosity of mortar also protects the pipe by reducing the amount (rate) of water that can contact the surface of the pipe. The water that permeates the mortar lining is essentially stagnant at the metal surface and the free calcium hydrate reacts with the carbonate and bicarbonate in the water to precipitate calcium carbonate on the pipe which also clogs the pores in the mortar and further limits diffusion of oxygen and chlorides to the surface of the pipe. Even when all of the excess alkalinity of the mortar has been consumed, the calcium carbonate that is precipitated on the metal surface acts to prevent further corrosive attack. The free lime in the lining also can react with any free iron ions from corrosion to form iron hydroxides that will also clog the porosity in the mortar and limit corrosive attack.

[9] Muster T.H. et al, Cement Mortar Linings in Cast and Ductile Iron Pipe: Life Expectancy and Dependence Upon Water, 18th International Corrosion Conference 2011, page 2.

2.1.2 Sulfates

It is significant that high sulfate waters are not typically more corrosive than high chloride waters.[10] According to Larson, this is because when high sulfates are encountered, the water generally has a high calcium concentration whereas when high chlorides are found, the water is generally high in sodium. The presence of sulfates, that have higher ionic strength than chlorides, would be expected to make the water more corrosive but this effect is offset by the additional calcium that is beneficial in the precipitation of scale and in autogenous healing of cracks in cement. Therefore, high chlorides waters are generally more corrosive than waters that are high in sulfates.

In many cases the attack of cement by sulfur species, in particular H_2S, results in a very soft and mushy surface. This heavy surface attack results in loss of CML thickness that is obvious and can be so aggressive that the presence of cracking becomes a secondary issue. Sulfate attack of the cement at the base of a crack where it can result in loss of alkalinity and corrosion of the steel is not as important of a mechanism as attack accelerated by other dissolved species such as chlorides.

Sulfates in the water attack cement by reaction with calcium hydroxide, formed during hydration of the CaO, and form gypsum; then the gypsum reacts with the tri-calcium aluminate in the cement matrix to form calcium sulphoaluminate (ettringite). Assuming sodium sulfate is dissolved in the water, the following reactions to form gypsum and ettringite are possible:[11]

$$\underset{\text{Sodium Sulfate}}{Na_2SO_4} + \underset{\text{Hyd. Lime}}{Ca(OH)_2} + \underset{\text{Water}}{2H_2O} \rightarrow \underset{\text{Gypsum}}{CaSO_4 \cdot 2H_2O} + \underset{\text{Caustic}}{2NaOH}$$

$$\underset{\text{Gypsum}}{3CaSO_4 \cdot 2H_2O} + \underset{\text{Tricalcium Aluminate}}{4CaO \cdot Al_2O_3 \cdot 19H_2O} + \underset{\text{Water}}{8H_2O} \rightarrow \underset{\text{Ettringite}}{3CaO \cdot Al_sO_3 \cdot 3CaSO_4 \cdot 32H_2O} + \underset{\text{Hyd, Lime}}{Ca(OH)_2}$$

Both gypsum and ettringite have expansive characteristics that damage the structure of the cement.[12] In general, the more sulfate resistant cements have reduced levels of excess calcium hydroxide and a limit of 5% for the tri-calcium aluminate hydration reactant. ASTM C150, type V cement is generally considered to be resistant to sulfates and this composition limits the tri-calcium aluminate to 5%. Many company specifications also call for reduced amounts of free calcium hydroxide in type V cement.

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[10] Larson, T.E. and Buswell, Calcium Carbonate Saturation Index and Alkalinity Interpretations, Journal of the AWWA, vol 34, No 11, Nov 1942, P 1677.

[11] Thomas, M.D.A. and Scalny, J., Chapter 24, Chemical Resistance of Concrete, Significance of Tests and Properties of Concrete and Concrete Making Materials, ASTM STP 169D, April 2006, p 258.

[12] Sulfate-Resisting Cements and Concrete, Cement Concrete & Aggregates Australia, p 1.

Table 2-2
Cement recommendations from ACI Committee 201.[13] *Although the typical cooling water used in power plants does not have high sulfate, the soil surrounding the pipe can have high sulfates.*

Exposure Class	Soluble Sulfate	Recommended Cement Type ASTM C150
S1, Negligible	<0.10% in soil <150 ppm in water	None
S2, Moderate (Seawater)	<0.20% in soil <1500 ppm in water	II or V
S3, Severe	<2.0% in soil <10,000 ppm in water	V
S4, Very Severe	>2.0% in soil >10,000 ppm in water	V Modified w Pozzolan

2.1.3 Oxygen

Oxygen is a required component in the corrosion of carbon steel in neutral to alkaline conditions. The use of a low water to cement ratio to produce dense concrete, such as that made by centrifugal casting of the CML, is beneficial in controlling diffusion through the cement. Corrosion of the reinforcement in the cement on the exterior of the pipe is also important and the use of good construction practices to maximize the density of the concrete to resist oxygen diffusion to the reinforcement level is beneficial.

Very low corrosion rates of steel have been observed even after the free lime alkalinity has been leached out of the mortar. This suggests that the cement acts as a barrier to oxygen diffusion. Cracks that extend to the metal surface make for easier access for oxygen diffusion and subsequent metal corrosion.

2.2 Alternating Wet-dry and Pressure Service

Alternating wet-dry service of CML piping is detrimental when the dry cycle is so long, generally measured in weeks, because the mortar is damaged when it becomes very dry. This is because the CML is alternately undergoing normal reactions with the formation of limestone, calcium gels, and other similar chemistry that depend on the cement mortar surface being wet with water, and then dry periods where the gels and similar chemical species that have formed dry out. Carbonation shrinkage[14] occurs to crack the cement and increase its porosity to water and chlorides.

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[13] ACI Committee Report ACI 210.2R, Guide to Durable Concrete (2001) American Concrete Institute, p 201.2R-10.

[14] ACI Committee 224 Report, Control of Cracking in Concrete Structures, Chapter 3, page 224R-3.

When the wet-dry cycle is rather short, such as 24 hours, Yang has shown that the cracks heal quite nicely.[15] This is probably because the water that is in the cracks has no time to significantly evaporate and this water has time to react with the free lime in the cement, dissolve CO_2 from the air, increase the water hardness in the crack, and then precipitate the healing limestone.

Alternating the water pressure inside of CML piping systems is also detrimental if the pressure fluctuation is substantial. As reported by McReynolds[16] et al, a large diameter pipeline undergoing a high, fluctuating stress loosened the cracks in the CML and prevented autogenous healing. In this case, the pressure varied daily from 250 to 300 psig and the diametrical expansion of the pipe was excessive and cracked the CML. The cracks in the CML continued to be opened with each pressure cycle until the arch effect holding the CML in place was lost and large pieces of the CML fell out exposing the steel to corrosion. A secondary cause of cracking could have been that the changing water pressure resulted in the pressure behind the CML being higher than the pressure inside the pipe and this difference in pressure forced the lining loose. Pneumatic pressure testing, if the pressure is reduced quickly, can also result in the ejection of pieces of the CML.

2.3 Stagnant Service and Microbiological Attack

Corrosion of the steel behind concrete can occur via MIC and the concrete itself can be damaged by MID. Microbiologically Induced Corrosion or MIC is the term used for corrosion of the steel behind the cement mortar lining whereas Microbiologically Induced Degradation (MID) is term used for the damage caused by bacteria to the cement. It is unlikely that MID will occur on the inside of the pipe unless both a continuously replaceed food source is available and a bacteria is also available that either uses calcium in its biology or excretes acidity to dissolve the cement. To date MID has not been reported to be a common degradation mechanism for CML pipe.

Stagnant and intermittent service can result in the diminishment of biocide addition and allow the bacteria in the water to grow. Many types of bacteria generate H_2S that converts to sulfuric acid in the crown (vapor phase) of the pipe as well as some bacteria generate sulfuric acid directly. All of these acid bacteria by-products attack and dissolve the cement and result in significant loss of CML thickness.[17] Such conditions can also occur in dead legs.

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[15] Yang, Y., Autogenous Healing of Engineered Cementitious Composites under Wet–Dry Cycles, Cement and Concrete Research 39 (2009), p 8.

[16] McReynolds, et al, Causes of Etiwanda Pipeline Lining Failure, submitted draft ver., 2 to AWWA (2013) p 8-9.

[17] Housewright M. et al, Preliminary Investigation of the Role of Bacteria in Concrete Degradation, MDOT Research Report RC-1444 (April 2004) submitted to the Michigan Department of Transportation, p 6.

2.4 Langelier Saturation Index

One of the original indicators for water that will dissolve cement is the Langelier Saturation Index (LSI). It is based on the pH value of service water vs. water that is saturated with calcium carbonate. The LSI was specifically developed to determine if concrete would corrode in water.[18]

$$LSI = pH - pH_s$$

When the pH of the water is less than the corresponding pH_S of a calcium carbonate saturated solution, the LSI will be negative. A negative index indicates that the water is corrosive and will dissolve calcium from the cement to form calcium carbonate that is dissolved in the water. When the LSI is positive, the pH of the service water is alkaline enough to prevent the dissolution of calcium and in fact will tend to deposit calcium. For any water, the more negative the LSI, the more aggressive the water is to cement.

The saturation pH for determining the LSI is a function of total dissolved solids (TDS), alkalinity, temperature, and calcium hardness. At the same time as the LSI is being determined, the concentration of free "aggressive" carbon dioxide should be determined. High concentrations of free carbon dioxide can also be used to determine the water aggressiveness to CML. The LSI is not applicable to brines where the salinity affects the solubility of calcium carbonate.

There are other calculation methods used to attempt to define the calcium carbonate precipitation reactions that control the degradation of cement. They are:

- Ryznar Index (RI) which is a modification of the LSI to produce only positive numbers
- Aggressiveness Index (AI) that was developed to predict the degradation of Asbestos Cement
- Calcium Carbonate Precipitation Potential (CCPP) is likely an improvement over the other indexes. It takes into account the effect of other dissolved ions, like chloride and sulfate, and how these ions change the precipitation of calcium carbonate. The recommended concentration of calcium carbonate in the water to both prevent leaching of the cement and allow for autogenous healing of cracks is 5 mg/liter or more.[19]

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[18] Dillon, CP, Materials of Construction for Once-Through Water Systems, MTI Publication No 43, p16.

[19] Sagues, A.A., Reinforced Concrete Pipe Cracks – Acceptance Criteria, Contract BDK84 – 977-06, Final Report to the Florida Department of Transportation, p 8.

None of the methods that have been developed are always accurate in the prediction of cement dissolution or autogenous crack repair, but the indication is that the CCPP may be the best method that is available today. In October 2013, a free spreadsheet for calculating the CCPP is downloadable from Trussel Technologies Inc.[20]

[20] http://www.trusselltech.com/downloads?category=6

Section 3: Installation Methods and Lining Quality

3.1 Centrifugal Lining

The best type of CML is installed by centrifugally casting the mortar into a spinning pipe that is also vibrated at the same time and is generally purchased to the AWWA C502 Standard.[21] The high speed of spinning and vibration compacts the mortar and eliminates much of the porosity. It also brings water to the internal surface to form a laitance layer that, when cured, is hard and of low permeability. This layer has a very high concentration of cement and is very resistant to aggressive water (e.g. soft water).

3.2 Projection Lining

The projection method uses a spinning head on the end of a lance that is inserted into the center of a stationary pipe. The cement is slung onto the pipe surface. After application, the surface is smoothed and compacted. The density of the lining is not as good as the centrifugal method and there is no cement rich laitance layer on the interior surface

3.3 In-situ Field Lining

The in-situ lining method can be done using a projection method, such as shotcrete, if the pipe is large enough for entry or for smaller pipe by using a spinning head pulled through the pipe on a dolly. It is used to reline pipe in place. Porosity of 1 mm in diameter is commonly encountered using this method. Fittings are made using in-situ methods that can even include hand application. Thus fittings are often lined with poorer quality mortar than the pipe and should be made with thicker linings to compensate for the decreased quality – but this is often overlooked. The AWWA C104 standard for ductile iron linings only requires 1/16 inch of mortar lining in both the pipe and fittings.

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[21] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Chapter 1, p 6.

3.4 Type of Cement

The more sulfate resistant cements are made with lower tricalcium aluminate content to minimize reactions with sulfate that decompose the calcium-aluminate- silicate hydration products. The sulfate resistant cements are also produced with higher levels of sulfate (typically in the 1 to 4% range) already in the cement. This makes a sulfate containing phase during initial hydration and curing. Because the cement then contains some stable sulfate reaction products, the driving force for more sulfate to diffuse into the cement pore water is reduced and the chemical resistance to sulfate is increased.

Section 4: Industry Standards

4.1 Effects of Pipe Age

Many of the piping systems with CML have been in service for more than 40 years and are still in good condition with the lower half of the lining still showing a good reserve of alkalinity. The factor that most effects the life of lining is the hardness or softness of the water. Also of prime importance is the thickness of the lining.

After the reserve alkalinity is lost, the lining is still in place but has lost its ability to self-heal. The CML is still able to protect the iron or steel pipe by acting as a diffusion barrier to the ingress of oxygen, chlorides and other ions that are needed to support the corrosion of steel in water. Often, the pH under the alkalinity depleted CML is still about 9. As time progresses, the pH under the depleted CML will become more acidic but at a rather slow rate. The time to actual leakage or failure of the pipe will depend on other factors such as the pitting rate under the CML, temperature of the water, oxygen content, episodes of low pH from malfunctioning pH control in recirculated systems, intermittent operation, operation partially filled, etc. An estimated pitting rate for normal, biocide treated once-through river or lake water, is 1/32 inch per year for the steel under the CML. It is believed that this rate is conservative since the rate for bare steel in generic service water is often estimated at 1/32 inch per year or less.[22]

Using the data from Muster, pipe specimens removed from service that were in water with an LSI of -0.9, showed good agreement between the phenolphthalein, pH and CaO determination in that there is a transition of the pH from 12 down to 9 at the metal/CML juncture that occurs in the range of 9 to 13% CaO. This is shown in Figure 4-1.

[22] Dillon, C.P., Materials for Construction for Once-Through Water Systems, Pub No. 43, Materials Technology Institute, 1995, p128.

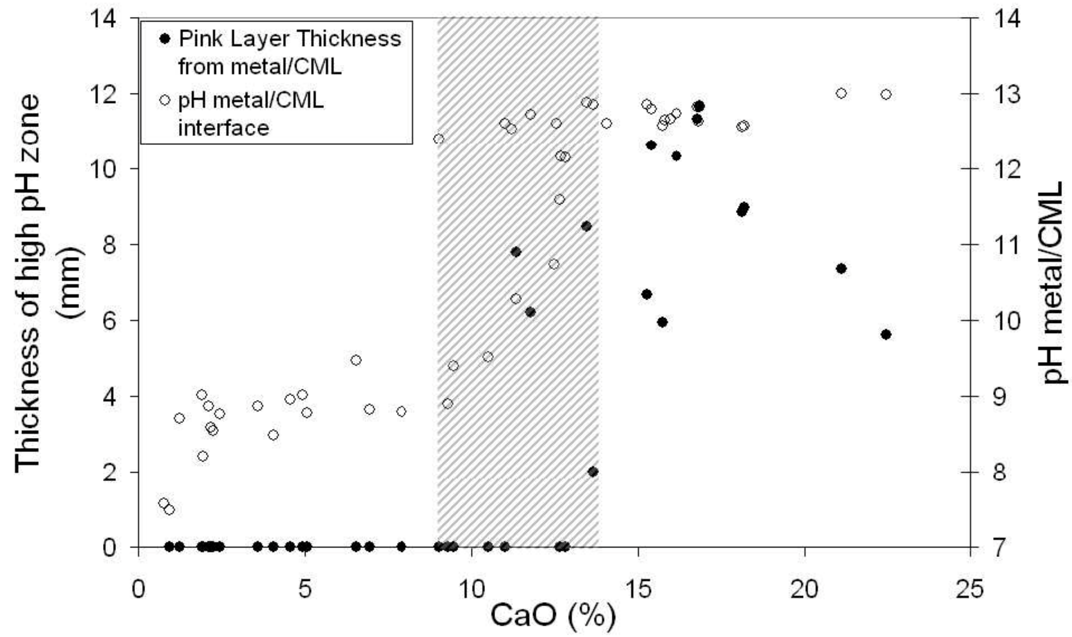

Figure 4-1
Comparison of CaO loss vs. thickness measured by phenolphthalein, pH determination and CaO (%).[23]

When the pH at the metal to CML interface is around 12, the steel will be passive and resist corrosion whereas when the pH falls to the 8.5 range, the steel will lose passivity and be subject to corrosion.

The pipe samples used to construct Figure 4-1 were from South Australia and had lining thickness of about 7 mm. The measured depletion rate was 0.125 mm/year suggesting that half of the cement CaO was reduced from above 12% to below 9% in about 30 years. Assuming this depletion rate, a life exceeding 50 years could be estimated.

4.2 Allowable Crack Size for Concrete Structures

The American Concrete Institute has much tighter allowable for crack widths than the nominal 1/16 inch for new pipe allowed by the AWWA C 205 standard – but this is for solid concrete that is not totally immersed or is in liquid service with a pressure that forces water completely through the thickness of the concrete. This is much more severe exposure than CML linings since the steel pipe wall blocks the flow of water and the stagnant water at the base of any crack can then undergo the chemical reactions to self-repair the defect.

[23] Muster, T.H, et al, Cement Mortar linings in Cast and Ductile Iron Pipes: Life Expectancy and Dependence upon Water Chemistry, 18th International Corrosion Conference 2011, 20-24 November 2011, Perth, Australia, Australia Asian Corrosion Society, p 7.

Table 4-1
Allowable crack widths for concrete structures (from ACI 224 [24])

ACI 224 Allowable Crack Widths	
Exposure Condition	**Allowable Crack Width, inch**
Dry Air or Membrane	0.016
Moist Air and Soil	0.012
Seawater and Seawater Spray, wetting and drying	0.006
Water Retaining Structure	0.004

4.3 Allowable Crack Width for CML in Various Standards

The AWWA C205 standard for carbon steel pipe requires new pipe from 4 inch to 10 inches in diameter to have a minimum CML thickness of 1/4 inch - plus 1/8 inch and minus 1/16 inch. This would imply that the minimum thickness could be as low as 3/16 inch. The standard also allows shrinkage cracks in the lining of up to 1/16 inch in width in new pipes of any diameter, even those with thicker linings under the assumption that 1/16 inch wide cracks would autogenously heal themselves via limestone precipitation. The cracks would normally be wedge shaped with the tip of the crack touching the inner wall of the pipe. Making the assumption that the width of the crack to the thickness of the lining is important, the calculation for a 1/16 inch wide crack in a lining that was 3/16 inch in thickness would result in a Crack Depth to Crack Width ratio (D/W) of 3:1.

Crack healing occurs mainly by diffusion of bicarbonate ions first into the crack mouth and then by further diffusion down to the tip of the crack. This causes the precipitation of the healing limestone, even when water is flowing at rates up to 15 ft/sec through the pipe. One option is to use the D/W ratio to predict the crack width allowable for thicker mortar linings. For example, for a new 1/2 inch thick lining, the same 3:1 ratio would allow a crack width of 0.167 inches, just a bit smaller than 3/16 inch. For a 0.167 inch wide crack to autogenously heal, the healing reaction could remove a significant amount of free lime in the mortar at the interface near the metal surface and reduce the "reserve" mortar pH to lower levels which would then make the pipe less resistant to corrosion of the steel years later. Thus, even if such a wide crack would heal itself, it will reduce the reserve alkalinity at the metal surface to shorten the time to the start of iron/steel corrosion.

The flowing water velocity will affect the turbulence of water deep inside the crack. Thus, the D/W ratio may not scale linearly for cracks wider than 1/16 inch. This suggests that the D/W ratio for cracks larger than 1/16 inches should be less than that what would be calculated for a 1/16 inch wide crack.

[24] Non Structural Cracks in Concrete, Concrete Technology and Codes – 29, From the U.S. NRC Web site, pbadupws.nrc.gov/docs/ML1215/ML12153A412.pdf - p 51.

The bigger question is the standard allowing a 1/16 inch wide crack in a lining of only 3/16 inch thickness. One might expect that this crack might not heal if the water flow through the pipe created enough turbulence at the bottom of the crack to prevent the concentration of bicarbonate ions necessary to raise the pH and cause the precipitation of limestone.

$$Ca(OH)_2 + HCO_3^- \rightarrow CaCO_3 + OH^-$$

The precipitation of limestone in this 3:1 D/W crack is probably assumed to occur under stagnant or low flow conditions and not under conditions of high flow and turbulence.

The AWWA standard for Ductile Iron Pipe, C104, allows the CML to be only 1/16 inch in thickness for pipe up to 12 inches in diameter. There is a section of the standard that allows for a double thickness of CML and this should be selected whenever possible. Obviously, for DI pipe built to the minimum standard, the reserve alkalinity to heal a significant crack is very low. There is no crack width defined as acceptable in the C104 standard for pipes smaller in diameter than 24 inches, but the crack length is limited to less than the pipe diameter. For pipes with diameters larger than 24 inch, the acceptable crack length must be shown to close and heal by continuous exposure to water. The comparable Australian standard limits the crack to no wider than 2 mm (0.08 inches) and to a depth of no more than half the thickness of the lining. [25]

Sahraman[26] reports that as far as chloride diffusion into cracks in the CML, no agreement has been reached on acceptable crack widths but reports that for seawater like chloride concentrations of 3% NaCl, cracks that are 50 microns (0.002 inches) or less in width will self-heal in 30 days and exhibit white traces where the cracks were located. The white traces were analyzed as calcium carbonate indicating that the transport of chlorides along narrow cracks can effectively block corrosion. Cracks that are wider than 135 microns (0.005 inches) are much more likely to experience corrosion of steel and have a reduced service life. Others referenced in Sahraman's paper suggest that cracks as wide as 0.004 inches will self-heal. The many differences in chloride transport and crack width findings are probably because many of the laboratory produced cracks are not the same physical shape as the V shaped cracks that form in actual practice. Crack widths that are allowable in structural concrete vary from 0.004 inches per ACI 224 to as wide as 0.013 inches per ACI 318.

Sagues's 2011 report to the Florida Department of Highways[27] suggests that cracks in reinforced concrete culvert pipe that are 0.020 inches in width will autogenously heal with up to 500 ppm of chlorides in the water environment and

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[25] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Chapter 4, p 66.

[26] Sahmaran, M., Effect of flexure induced transverse crack and self-healing on chloride diffusivity of reinforced mortar, J Mater Sci (2007) 42, p 9135.

[27] Sagues, A.A., Reinforced Concrete Pipe Cracks – Acceptance Criteria, Contract BDK84 – 977-06, Final Report to the Florida Department of Transportation (2011) p 73.

at this level of chlorides, very little corrosion of the pipe reinforcement will occur. He also proposed a more relaxed criterion for cracks with up to 2000 ppm of chlorides in the environment and suggests that this criterion would also be suitable.

Since ASHTO (2006) allows cracks up to 0.100 inches in width with the external environment containing 500 ppm of chlorides, Sagues proposed a sliding scale factor, F_s to be applied against the per-determined projected lifetime that incorporates crack widths from 0.020 to 0.100 inches with chlorides up to 2000 ppm. This factor is multiplied by the projected pipe life and is designed to reduce the projected pipe life to zero if a crack is 0.100 inches wide.

$$F_s = (0.100 - W_a) \div 0.080$$

Fs is the design factor and Wa is the measured crack width measured in inches.

Although this data relate to internal cracks in the CML, it does appear to be quite useful in predicting the life of the external cement coating if the soil is saturated with enough water to keep the pipe wet.

4.4 Through-wall Cracks in Solid Concrete

In contrast to the ACI 224 requirements, cracks up to 0.015 wide will generally seal in thick, solid concrete pipe where water is slowly flowing through the crack. This is because such tiny cracks are very circuitous, the pressure drop through such small cracks is high, the cracks clog with solids, and the flow of water through the crack is quite low. Additionally, the stagnant arms of these fine cracks allow for the stagnant water containing bicarbonate ions to increase the calcium concentration and pH rather quickly which causes the precipitation of limestone – calcium carbonate. Limestone then precipitates on the newly formed crystals until the crack is sealed. Since CML pipes, even with cracks, do not allow water to flow through the cracks, this criteria is likely to be very conservative when applied to CML piping.

4.5 External Corrosion of Mortar Coated Steel Pipe

4.5.1 Construction

The external layer of cement-mortar is called a Cement-Mortar Overcoat if it is put over an epoxy coating and Cement-Mortar Coating if put over steel without a coating. Steel pipe made in accordance to AWWA C502 is the most common product.

- If the steel pipe has been externally coated with a dielectric coating such as epoxy, the overcoat of mortar-cement is applied in two steps of 3/8 inch (equal) thicknesses with the reinforcement installed between the two applications.
- If the mortar-cement coating is applied over bare steel, the thickness is still required to be ¾ inch and the reinforcement is placed in the middle third of

the cement-mortar and the application of the cement-mortar can be done in one or more steps.

The reinforced coating will increase the strength of the composite pipeline for resisting crushing loads that could cause cracks in both the internal CML and the external cement-mortar coating. The reinforcement also helps keep the cement coating in place during construction, functions as a rock shield, and increases the weight of the pipe. The metal reinforcement can be bare steel, zinc plated steel or zinc galvanized steel.

Galvanized reinforcement is compatible with the cement mortar that is used on the outside of the pipeline and will increase the corrosion resistance of the wire or mesh. The use of galvanized reinforcement is common in the reinforced concrete industry and helps in resisting the corrosion from chloride salts. In general, the corrosion resistance increase of hot dipped galvanized zinc coatings is at least 2 to 3 times better than that of bare steel. Zinc plated steel increases the corrosion resistance somewhat less than galvanizing does since the thickness of the zinc plating is less –increasing the corrosion resistance to perhaps 1.5 times that of bare steel. When the zinc does start to corrode, the zinc corrosion products are less voluminous than those of iron and diffuse into the cement matrix to minimize the pressure of the corrosion products in splitting the cement.[28]

4.5.2 External Cathodic Protection

Since the reinforcement may not be electrically continuous with the steel pipe, cathodic protection of the outside of the pipe could result in damage to the coating from stray-current corrosion of the reinforcement. When the reinforcement is corroded by stray-currents, the rust corrosion product is about 6 times more voluminous than the steel wire and this increase in volume will crack and spall the coating. In addition, if the steel pipe sections that make up the pipeline are not electrically continuous with the other sections of pipe that make up the pipeline, stray current corrosion at the joints will occur. To make the pipeline electrically continuous, the joints must be welded together or, when mechanical joints are used, wire jumpers must be welded across the joints and all of the reinforcement must be electrically continuous with the pipe.

If cathodic protection induced stray current corrosion of the wire or mesh reinforcement does occur, cracking (or spalling) of the cement coating will result because of the formation of a voluminous rust layer inside the cement coating. These cracks will lower the crush strength of the composite pipe (inner CML, steel pipe, and the external cement coating) that could result in cracking of the inner lining. When the corrosion of the reinforcement is bad enough to spall the cement coating, loss of the structural strength supplied by the reinforcement will occur within a few years. Even when the reinforcement is lost to corrosion, the lower part of the coating that was between the reinforcement and the steel pipe is

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[28] Fratisi R., Part 1 Preventative Measures, 1.4 Galvanized Steel Reinforcement, Corrosion of Steel in Reinforced Concrete Structures (2003) COST Action 521, EUR 20559, p 38.

likely to be still in place and will still protect the external surface of the pipe from corrosion. If the reinforcement was not needed for strength, the pipe can be considered to be in serviceable condition. Obviously, if the reinforcement was needed to resist pressure and crushing loads, the pipe is in serious condition and replacement or repair is warranted.

If the external reinforcement and the pipe sections are all electrically connected (continuous) the use of cathodic protection will significantly increase the life of the pipe on the outside – even if large cracks are present. Thus, cathodic protection can be beneficial, but only if stray current corrosion caused by electrically isolated reinforcement or pipe sections, is avoided.

Section 5: Techniques to Evaluate Cracks and Steel Corrosion

5.1 Evaluation with the CML in Place

The following four techniques can be used to examine the interior of buried pipe:

- Visual examination (direct assessment) is the primary technique for the evaluation of CML[29]. This can be done by direct entry or with the use of a robot. The color of the surface of the CML is very useful in locating cracks and other damage. Scale on the interior lining may indicate that the water chemistry is scaling and this could be a good indication that the cement is not degraded. Simple tools can be inserted into to cracks to check for depth and rulers can be used to determine width.
- Hammer Test and Impact Echo are techniques that are used to find loose linings and areas of porosity. The hammer test is not quantitative but relies on the experience of the technician to locate unbounded areas and areas of porosity and delamination. Impact-echo is a more quantitative method for nondestructive testing of concrete and masonry structures that is based on the use of calibrated impact-generated stress (sound) waves that propagate through concrete and masonry and are reflected by internal flaws and surfaces. Impact-echo can be used to determine the location and extent of flaws such as cracks, delaminations, and voids.[30]
- Electrochemical Potential using a copper-copper sulfate reference electrodecan be used to indicate the condition of the steel pipe and reinforcement.
    - More positive than -200 mV, a 10% chance of underlying steel corrosion.
    - More negative than -350 mV, a 90% chance of underlying steel corrosion.[31]
- Diffuse Ultrasonic is another method to look for cracks.[32]

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[29] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Chapter 3, p 31.

[30] Sansalone, M.J. et al, The Impact-Echo Method, NDTnet Feb. 1998 , Vol.3 No.2.

[31] Kurtis K., Cracking in Concrete Part I: Causes and Part II: Effects (2013) Georgia Institute of Technology, slide presentation, www.ing.puc.cl/ingenieria-y.../wp.../kurtis-cracking-and-durability.pdf , slide 43.

5.2 Removal of a CML Specimen

Phenolphthalein examination requires that a section of the CML be (destructively) removed from the pipe. Examination of the cross-section of this piece of CML is a rather simple and easy way to determine the extent of calcium leaching. It is done by spraying the cross section with the indicator solution and measuring the depth where the color goes from clear to pink. The indicator turns pink when the pH is 9 or higher indicating that the basic nature of the residual CaO still present in the matrix and the corrosion resistance offered to steel by alkali is still present.[33] This technique is outlined in Appendix A.

As an example, the lime depletion rate, as measure by phenolphthalein, for 16 and 19 inch diameter steel pipes with 1/2 inch thick layer of mortar exposed to water with a negative Langelier Index of -1.3, was 0.004 inches per year.[34]

Direct pH measurement of layers of the CML can be done by drilling samples from the inside of the lining.[35] The samples are then ground into a powder and added to distilled water to extract any residual alkalinity and the pH of the water measured. This method is likely much more accurate than the phenolphthalein test but is time consuming.

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[32] Shokouhi, P., Monitoring of Progressive Microcracking in Concrete Using Diffuse Ultrasound, 6th European Workshop on Structural Health Monitoring - Tu.3.B.3 (2012) p 1.

[33]Life Expectancy of Cement and Mortar Lining in Cast and Ductile Iron Pipes, Water Research Foundation (2011), Chapter 6, p 81.

[34] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Chapter 3, p 40.

[35] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Appendix B, p 133-134.

Section 6: Guidance

Until better information can be developed, the following techniques can be used to evaluate the acceptability of existing cracks in cement mortar linings.

6.1 Crude Estimation of Acceptable Crack Widths

Knowing just the CML thickness, the Langlier Index for the water and an educated estimation of the expected life of the pipe system, the following information can be used to develop a multiplier to estimate the life of the CML containing cracks. The lifetime of mortar linings is so variable that being able to predict the actual time based upon samples removed from service from many different water supplies is not possible. This lack of agreement is confounded by the actual pH of the mortar, chloride content of the water, temperature, initial CaO concentration, aggregate/cement ratios, CML porosity, and the methodology used to measure the CaO concentration at the metal surface. Evaluation of a sample removed from the system under investigation can help to minimize these variables.

Table 6-1
Effect of the Langelier Index and CML thickness on the time to depletion of the residual alkalinity in the lining for water with a pH between 6.5 to 8.5.

Langelier Index	Lining Thickness	CML pH Depletion Lifetime, Arbitrary Year Units
Less than -3.0	Less than 1/16 inch	2
	1/16 to 1/8	5
	1/8 inch to 1/4 inch	15
	1/4 inch to 1/2 inch	33
	1/2 inch to 1 inch	70
-3.0 to -1.0	Less than 1/16 inch	4
	1/16 to 1/8	9
	1/8 inch to 1/4 inch	20
	1/4 inch to 1/2 inch	41
	1/2 inch to 1 inch	90

Table 6-1 (continued)
Effect of the Langelier Index and CML thickness on the time to depletion of the residual alkalinity in the lining for water with a pH between 6.5 to 8.5.

Langelier Index	Lining Thickness	CML pH Depletion Lifetime, Arbitrary Year Units
-1.0 to +3	Less than 1/16 inch	5
	1/16 to 1/8	11
	1/8 inch to 1/4 inch	24
	1/4 inch to 1/2 inch	50
	1/2 inch to 1 inch	100+
+3 and higher	Less than 1/16 inch	7
	1/16 to 1/8	15
	1/8 inch to 1/4 inch	35
	1/4 inch to 1/2 inch	75
	1/2 inch to 1 inch	100+

The information in Table 6-1 can be used to estimate the life of the CML – at least to the point where the reserve alkalinity of the CML has been depleted. One method to use the Arbitrary Year Units in Table 6-1 follows:

- If the existing CML pipe has a known and satisfactory history, for example the pipe is 13 years old and has had no leaks, no pieces of the CML have shown up in the basin of the cooling tower, and a single, cursory visual internal inspection shows no gross and obviously missing mortar lining, then the Arbitrary Year Units could be ratioed to increase the projected life of the CML. For example, use the data for the next thicker lining and multiply the estimated life by this ratio.

  Example: For a CML pipe in water with a Langelier Index of < 3.0 and a thickness between 1/16 inch and 1/8 inch, and if there is no history of degradation, multiply the forecast depletion lifetime by 15/5 = 3 or the ratio of the depletion lifetime for the next higher thickness divided by the depletion lifetime for the known thickness. Using this factor of 3, we would then forecast the depletion lifetime to be 5 x 3 = 15 years.

- If no observation/history of the lining is known, simply use the Arbitrary Year Units as years.

At the expiration of the lifetime of the CML alkalinity, corrosion of the steel pipe can be assumed to have started. Using the corrosion rate of steel in the particular water system, a forecast of the life of the pipe can be approximated. If the rate of corrosion of bare steel in the water system is unknown, a default value of 1/32 inch per year should be used as the corrosion rate of the steel pipe.

6.2 Estimation of Acceptable Cracks Widths with More Information

6.2.1 Acceptable Crack Widths for the CML

If the mortar thickness, chloride concentration in the service water, Langelier Index, Mortar pH and flow rate are known, the Tables 6-2 and 6-3 can be used to predict cracks widths that are likely to autogenously self-heal.

Table 6-2
Parameters related to CML self healing. Sum one cell from each heading category to determine allowable crack width.

Mortar "t" inches	Chloride, ppm			LSI			Mortar pH			Flow Rate, ft/s		
	<250	250 to 1000	1000 to 1000	<-1.3	-1.3 to +3.0	>+3.0	Unknown	<11.5	>11.5	Stagnant	<7	>7
<250	0.2	0.0	-0.2	-1.0	0.0	1.0	-0.6	-0.6	-0.2	-0.3	-0.1	0.0
1,000 to 10,000	0.3	0.1	-0.1	-0.5	1.3	1.5	-0.3	-0.3	0.2	-0.2	0.2	0.1
>10,000	0.4	0.2	0.0	0.0	0.5	2.0	0.0	0.0	0.7	0.0	0.6	0.2

Table 6-3
Sum of CML Parameters vs. Acceptable Crack Width for Internal Cracks

Sum of Four Categories	Allowable Crack Width (in)
< -1.5	1/64
-1.5 to -1.0	1/32
-1.0 to +1.2	1/16
> +1.2	1/8

Example: Mortar thickness 1/4 to 1/2, <1000 chlorides, LSI <-1.3, pH>11.5, flow >7 ft/sec.

Sum Equals = 0.1 + -0.5 + 0.2 + 0.1 = -0.1

Thus a 1/16 inch crack is acceptable

6.2.2 Acceptable Crack Widths for Exterior Cement Coatings

This same logic can be used for cracks in the external cement coating with the understanding that cracks on the external surface will not be very easy to locate or accurately characterize since the pipe will have to be uncovered and cleaned for inspection. If a crack is discovered that has already self-healed, the use of the measurement of the width of this autogenously healed crack will be better information than can be generated by using Table 6-4. If a crack is discovered that has active corrosion of the steel at the tip of the crack, this too will be valuable in defining maximum allowable crack size.

The cement mortar coating on the external surface will be a minimum of 3/4 inch in thickness with metal reinforcement located at roughly the center of the mortar coating. If damage if found, a likely scenario is that the cement that is located outside of the metal reinforcement will have spalled or cracked off while the cement beneath the reinforcement will be in-place and simply cracked. To evaluate external cracks, the Tables 6-4 and 6-5 can be used to determine the parameters for an acceptable crack width. The Langelier Saturation Index should be that of the ground water.

Table 6-4
Parameters related to self healing of cracks in exterior concrete coatings. Sum one cell from each heading category to determine allowable crack width.

Coating "t" inches	**Chloride, ppm**			**LSI**			**Mortar pH**	
	< 250	**250 to 2000**	**2000 to 10000**	**<- 1.3**	**-1.3 to +3.0**	**> +3.0**	**< 11.5**	**> 11.5**
External t >1/2	0.5	0.4	0.1	0.1	0.5	1.5	0.0	0.7

Table 6-5
Sum of Parameters vs. Acceptable Crack Width for Exterior Cracks

Sum of Four Categories	**Allowable Crack Width (in)**
0.2 to 0.5	1/32
0.5 to 0.8	1/16
0.8 to 1.7	0.1
1.7 to 2.3	1/8
> 2.3	5/32

Section 7: Research Needs

The following research would greatly improve our ability understand crack widths that autogenously heal, to forecast damage, and to plan for replacement.

- One need is to be able to accurately predict the ability of cement to autogenously heal with only knowing the water chemistry, the temperature, the pH, and the chemistry of the cement. The CCCP prediction attempts to encompass the water chemistry and the ability to precipitated calcium carbonate but even it does not account for the many more species that can be in the water. None of the models use an accurate analysis of the cement to be able to predict the precipitation of species onto the unique particles in the cement. With the current use of computer modeling, it should be possible to make thermodynamic and reaction rate calculations that include all of the ionic species in the service water (or the water on the exterior of the pipe) and to incorporate the solid species present to give a strong basis upon which to predict CML and cement coating healing and, perhaps, even the rate of degradation.
- The crack depth to width ratio, especially for wide cracks, is important to understand since the "edge affect" of water flowing past a crack will cause turbulence to some unknown depth inside the crack. Orientation of the crack in the pipe wall could very much determine the likelihood of autogenous healing since longitudinal cracks may be more affected by flow than radial cracks. Wide cracks that extend to the steel pipe surface in thin cementitious linings are more apt to not autogenously heal. This is because turbulence of the water may extend to the bottom of the crack and the build-up of the necessary calcium concentration to cause protective precipitation may not occur. This effect of crack width/depth ratio along with crack orientation and water flow rate needs to be investigated and understood so that a better prediction of crack W/D ratio could be used to determine acceptable crack sizes.
- A non-destructive examination tool that could be moved through the pipe to examine 100% of the pipe wall under the CML would be of benefit. The ideal tool would need to measure corrosion of all the pipe surfaces under the CML and be able to measure damage to reinforcement in the cement coating on the outside of the pipe. This tool would provide thorough inspection of the piping from the inside of the pipe. The alternative inspection by excavation (direct assessment) of sections of the pipe does not inspect 100% of the cement coating but instead is limited to small sections that can be

conveniently be accessed. A NDT tool as described could remove any doubt to the serviceability of the pipe.

Section 8: Conclusions

- Cracks in CML and in the concrete coating are a given and can be expected. Cracks can form during the setting and curing of the CML in the pipe and are often the result of cement shrinkage during the curing steps. Cracks can also form in both the CML and cement coating from excessive internal pressure and excessive external loads causing the pipe to ovalize or bend. If the cracks are continuously opened and closed by operational stresses, they cannot heal because the precipitated calcium carbonate is re-cracked during each cycle.
- The width of a crack that can heal in new pipe can be as wide as 1/16 inch and still autogenously heal if the water chemistry will cause precipitation and growth of calcium carbonate in the crack. For pipes that have been in service for a number of years and have had most of the CaO leached from the cement, the cracks that will heal should be less than 1/16 inch wide since the pH increase needed at the base of the crack may not be high enough to cause voluminous growth of the calcium carbonate faster that the corrosion of the steel pipe. Cracks that exceed 1/16 inch in width are more likely to not heal since crack orientation and crack width/depth ratio are likely critical elements without good answers. Cracks in the CML that are thinner than 1/8 inch, extend to the pipe surface, and have a depth to width ratio of less than 4:1 are not likely to heal. Corrosion of the steel carrier pipe would then ensue even if the service water is pH neutral to slightly alkaline.
- Autogenous crack healing in the exterior cement coating is more difficult to predict since the water chemistry and time of wetness on the outside surface is not as well known at the on the interior. Stray current corrosion will exacerbate corrosion of the pipe and reinforcement if it is not electrically continuous with the pipe. The corrosion products that form on the reinforcement and pipe will be voluminous and will crack the cement coating. If the external water and gas diffusion chemistry is able to precipitate calcium carbonate, cracks as wide as 1/16 inch are very likely to autogenously heal if the cracks are not routinely reopened from alternating external stresses. If the pipe is fully immersed in stagnant water, cracks orientation is not an issue. Given similar water chemistry, external cracks wider than 1/16 inch are more likely to heal than if they were inside the CML since the water is not turbulent and calcium build up should happen quicker.
- Questions that can be used to develop improved criteria for crack evaluation are included in Appendix B.

Appendix A: Phenolphthalein Test for Cement-mortar Linings[36]

This test will help to determine the extent or depth of the loss of protective free lime and calcium hydroxide that is leached when a mortar reacts with CO_2 and bicarbonate. When applied to the thickness of a mortar sample, it will turn pink indicating residual alkalinity is still present in the material. At a pH greater than 12 and below 8.2 to 9, the phenolphthalein is colorless.

A new, full thickness sample of CML will indicate a pink color through the full thickness. A CML that has been subject to significant cement leaching in service is likely to develop a pink color across just a portion of the full thickness. This test can be used to determine how deep the CML has been damaged.

The phenolphthalein indicator to be is used is 0.5% phenolphthalein in a 50:50 mixture of water and ethanol.

Technique:

1. Expose a fresh cross section of the CML taken from the pipe.
2. Spray a thin mist of the indicator on the surface of the cross section and wait about 1 minute.
3. Measure the depth of where the color changes to pink.

The boundary where the color changes from clear to pink delineates the depth of leaching.

[36] Life Expectancy of Cement Mortar Linings in Cast and Ductile Iron Pipes, Water Research Foundations, CSIRO, 2011, Appendix A, p 91.

Appendix B: Questions to Use to Rank Pipe for Inspection

Use the same questions to compare two or more piping system for determining which should be inspected first. Not all questions will be applicable. These questions omit normal safety issues.

Does the CML exhibit open cracks?

Does the CML exhibit healing with whitish looking healed cracks?

Is CML rusty looking indicating that iron corrosion may be taking place?

Are the cracks rusty looking and without a tight seal?

Is the Langelier Index below -1.0 indicating that calcium depletion will occur?

Is there >5 ppm of free carbon dioxide in the service water?

Is the water velocity > 15 ft/sec?

If cracked, is the crack 1/16 inch wide or less on ID surface?

Is the crack less than 0.08 inches wide and less than half way through the CML?

For a crack no wider than 1/16 inch, Is the width to crack depth (W/D) ratio 4 or more?

Is the crack less than 1/16 inch wide?

Is the crack between 1/16 and 1/8 inch wide?

Is the lining thickness 1/16 or less and not ductile iron?

Is the lining thickness greater than 1/8 inch and the pipe DI?

Is the CML in the fittings thicker than the pipe?

Is the CML made of Type I cement?

Is the CML made of Type II or IV cement?

Is the interior of the CML coated with a bitumastic or sealing compound?

Does the phenolphthalein Indicator show alkalinity for >1/2 the CML thickness?

Does the depth of $Ca(OH)_2$ loss in the lining exceed 1/2 the CML thickness?

Is the pH of the service water between 4.5 and 6.0?

Is the pH of the service water greater than 6.0?

Are the chlorides in the service water more than 25 ppm?

Are the chlorides in the service water more than 250 ppm?

Is the service water seawater or brackish water?

Is the service water treated with biocide to control MID/MIC Corrosion?

Does the service water contain sulfates < 150 ppm?

Does the service water contain sulfates > 250 ppm?

Is the CML type V to resist seawater?

Is the pipe line electrically continuous?

If a concrete coating is used on the exterior of the pipe, was it used in the calculation for crushing loads in the design?

If there is an external coating, is the reinforcement electrically continuous with the steel pipe?

If there is an external coating, is the reinforcing wire galvanized?

Is the external surface of the pipeline under cathodic protection?

Is the external surface of the pipeline subject to stray current corrosion?

Is the service water stagnant?

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com