

1 Epoxy Coating

1.1 Polymeric Coating System for Large Sewer Pipes and Manholes

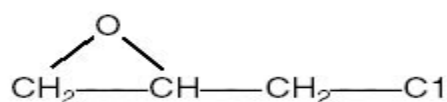
- Polymeric resins and mortars are widely used as a protective substrate in high corrosive system due to their good mechanical properties and corrosion resistance.
- Large sewer pipes are defined as pipes with diameters > 0.9 m.
- Polymeric coatings may be applied with other components including surface repair materials and primers. The coating system is shown in Figure 1.

Surface Repair Material	Primers	Polymeric Coatings
<ul style="list-style-type: none"> • Guniting • Shotcrete 	<ul style="list-style-type: none"> • Moisture blocks • Bonding agents 	<ul style="list-style-type: none"> • Epoxy/Epoxy Mortars • Polyurethane • Polyurea

Figure 1: Polymeric Coating System

Epoxy/Epoxy Mortar

- Epoxy and epoxy mortars are both thixotropic resins with high chemical resistance. Epoxy resins could be used as 100% polymer or as a mortar where fine aggregates (e.g., sand) are incorporated within the epoxy resin.
- The epoxy system consists of two parts, the resin and hardener (curative agent)
- The resin used in making epoxy is a chemical called epichlorohydrin (organic chemical containing epoxide and chlorine)



Epichlorohydrin

- The type of epoxy formed depends on the epoxide content or number. This is the number of epoxide equivalents in 1 kg of resin (Eq./kg).
- The hardener can include bisphenol A bisphenol F (the letter refers to one of the reactant, A : acetone and F: formaldehyde)

- The epoxy resin is cross-linked or cured with the hardener (or curatives) usually in a stoichiometric ratio to form the hard thermoset structures
- Epoxies are blended with additives, plasticisers and filler to achieve the required properties
- The types of epoxy typically used for coating are named according to the hardener used:
 - Epoxy A (Bisphenol A epoxy resin)
Formed from reacting epichlorohydrin with *bisphenol A* to form diglycidyl ethers of bisphenol A (DGEBA).
 - Epoxy F (Bisphenol F epoxy resin)
Reaction is similar to Epoxy A but using the hardener *bisphenol F*.
Compared to DGEBA, bisphenol F epoxy resins have lower viscosity and a higher mean epoxy content per gram. This gives them increased chemical resistance when cured.
 - Novolac epoxy resin
Novolac are formed from the reaction of epichlorohydrin with phenol-formaldehyde resin. These have high epoxide functionality (2-6) that forms a highly crosslinked polymer network displaying high temperature and chemical resistance, but low flexibility.

1.2 Actions

- When epoxy resin is applied in the rehabilitation of corroded concrete, it behaves as a 'permanent coating'. This term is used to indicate the physical means by which the coating will degrade. Unlike concrete and cement coatings that corrodes and will become thinner with time the epoxy holds much of its shape, although it can still be distorted by acid and microbial attack.
- Epoxy and epoxy mortars may provide protection against corrosion by the following pathways:
 - Epoxy resins have very low acid and moisture permeation rates (10^{-13} to 10^{-9} cm²/s) providing adequate barrier to acid.
 - The rate of permeation is determined by the type of epoxy used and the properties of the filler.
 - The more cross-linked the epoxy, the greater the chemical resistance.
 - Some epoxy resins are hydrophobic (hates water) and would therefore repel both moisture. This effect only occurs initially as the

hydrophobic property will change with acid attack of the epoxy network.

- The aggregate in epoxy mortars provides a tortuous path for the acid/moisture. This means it will take longer for the acid to permeate through the coating if it has to permeate around the aggregates. The greater the distribution and the finer the size of the aggregate the longer it will take for the acid to get through the coating.

1.3 Application

To select protective coatings for large pipes and manholes, the water utilities have implemented three strategies that include:

- Coating Specification
- Short Term/Accelerated Test
- Long Term Field Test

These are described below along with new performance models that have been developed under SP2 that could be used for coating selection and in the design of protective coatings.

1.3.1 Specifications

- There are only a few coating specifications that are relevant to the water utilities in Australia and currently they lack commonality.
- The list of current coating specification used by the Australian water utilities are listed in Table 1 (*Note specification from Queensland water utilities were not included in this study*).
- Figure 2 shows the corresponding qualification criteria by the Australian water utilities.
- Table 2 shows the specification in the US and UK. The UK specifications are based on coating selection for water mains.
- ASTM was in the process of developing an international standard to evaluate high performance protective coatings for sewer environment. The testing involves accelerated chemical testing, which only recognises the effect of sulphuric acid in the liquid phase and H_2S , CO_2 and CH_4 in the gas phase (ASTM 2011).
- The specifications are based mainly on acid resistance and may include: i) the compositional, chemical and physical requirements, ii) specific short term and

long term performance and iii) testing required to validate conformance to the required qualifications.

- The specification should include criteria that focusses on lining adhesion.

Table 1. Coating Specifications in Australia

Water Utility	Specification	Date Issued
Sydney Water Corporation	AM SS204 - Rehabilitation and corrosion protection of sewers using epoxy coating	July 1 2009
Sydney Water Corporation	SPEC 210 Corrosion Protection and Rehabilitation of Maintenance Holes	January 17 2013
SA Water, Water Corporation, Melbourne Water Corporation	APAS (Australian Paint Approval Scheme) Specification 214 - Coatings for Concrete Used in Sewage Works	October 23 2003
SA Water Corporation	TS 137 - Rehabilitation of Concrete Wastewater Manholes	April 2010 (updated in 2011)

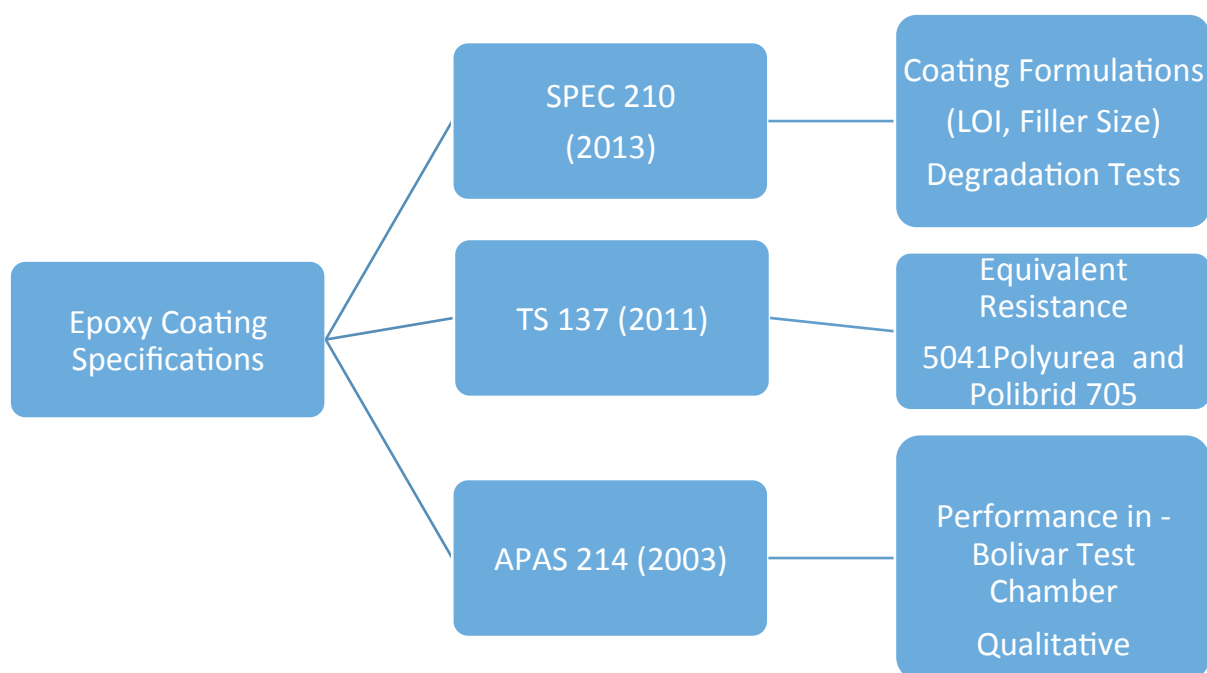


Figure 2. Chemical Resistance Qualification Based on Specifications

Table 2. Coating Specifications in the US and UK.

Country	Type of Coating	Specification	Date Issued	References
US	Epoxy	Standard Cement Materials NASSCO (National Association of Sewer Service Companies) Specification for Applying A Protective High Build Epoxy Coating to a Concrete Sewer Manhole	NA	http://www.nassco.org/publications/p_spec_guidelines.html
US	Epoxy, CAC	Rummel, Klepper, Kahl, LLP, Sewer Manhole Rehabilitation, Blue Plains Influent Sewer Rehabilitation	January 18 2009	http://www.ullimanschutte.com/documents/projects/Blue%20Plains%20Sewer%20Rehab/Specifications/02707%20Sewer%20Manhole%20Rehabilitation.pdf
US	Epoxy	City of Savannah: Section 02555 Protective Coating for Existing and New Concrete and Masonry Sanitary Sewer Structures		http://www.ci.savannah.ga.us/spr/SPRGuide.nsf/DocID/27139AA74AA17AA5852568A90060F060/\$FILE/02555-4-14-11.pdf
US	Epoxy	EPA/600/R-11/017 Quality Assurance and Quality Control Practices for Rehabilitation of Sewer and Water Mains	February 2011	http://www.epa.gov/nrmrl/pubs/600r11017/600r11017.pdf
US	Epoxy	ANSI/AWWA C620-07, AWWA Standard for Spray-Applied In-Place Epoxy Lining of Water Pipelines, 3 In. and Larger		http://www.awwa.org/publications/MainStreamArticle.cfm?itemnumber=35303&showLogin=N
	Epoxy	Standard to Evaluate High Performance Coatings for Sewer Systems	Proposed Nov 16-17 2011	http://www.astmnewsroom.org/default.aspx?pageid=2591
UK	Epoxy	WIS 4-02-01 - Operational Requirements: <i>In Situ</i> Resin Lining of Water Mains (UK Water Industry)	March 31 2007	http://www.water.org.uk/home/member-services/wis-and-ign/archived-documents/wis-4-02-01.pdf
UK	Epoxy	IGN 4-02-02: Code of Practice: <i>In Situ</i> Resin Lining of Water Mains (UK Water Industry)	March 31 2007	http://www.water.org.uk/home/member-services/wis-and-ign/archived-documents/ign-4-02-02.pdf

1.3.2 Design

- Historically the design of coating is based on lining thickness. The specific thickness has been based on advice given by consultants and coating manufacturers.
- Acid permeation models have been developed under the SP2 program to predict permeation depth as a function of time, environmental conditions and properties of coatings. The functions of these models include:
 - Comparison of coating performance based on their properties
 - Coating selection to fit a specific environmental conditions
 - Design coatings for specific service life
- The basic structure of the model is shown in Figure 3.

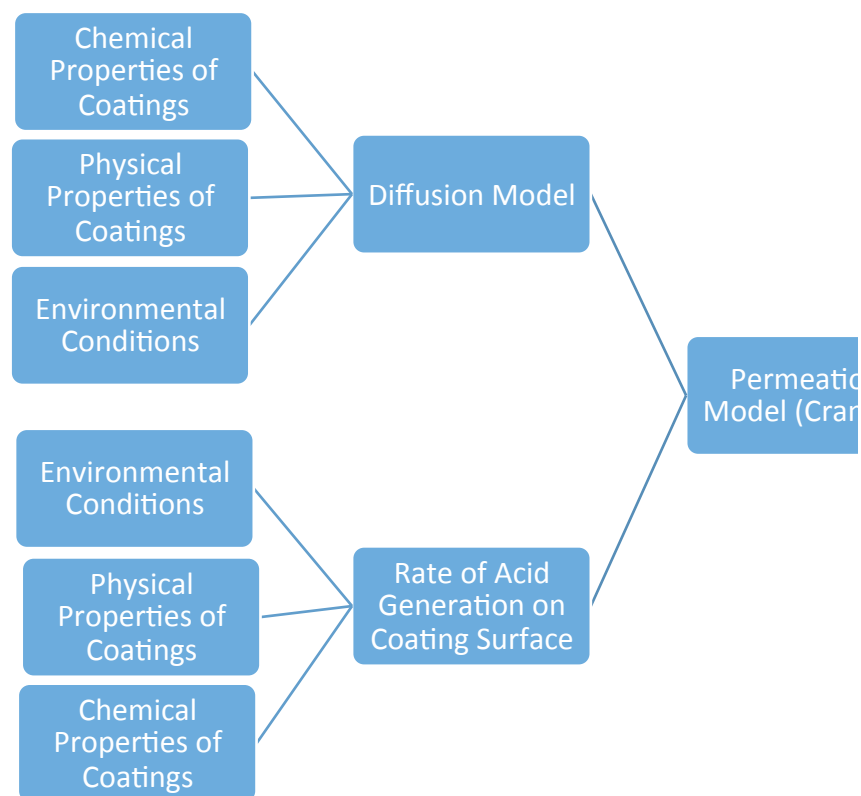


Figure 3. Basic structure of the acid permeation model

- The permeation model (based on Crank's equation) needs to be selected based on the dependency of surface acid concentration (pH) and diffusion with time (D_c). The two types of dependency are shown in Figure 4 as stage 1 and stage 2.

- Stage 1 represents short term service and shows the surface pH is varying with time.
- Stage 2 represents the longer term condition of the coating and the surface pH has become constant.
- The diffusion coefficient in both stages 1 and 2 continues to vary with time, although in stage 1, the change is more significant.
- Table 2 shows the Crank equations (permeation model) that must be used based on prediction of coating performance based on short term (stage 1) and long term (stage 2) acid permeation.
- Example of validation of the permeation models over short and long term durations are shown in Figures 4 and 5.
- A copy of working models (in excel) are available from the Score project relevant for Sydney, Melbourne and Perth sewers. Typical environmental conditions, coating properties of selected coatings are included in the excel spreadsheet.

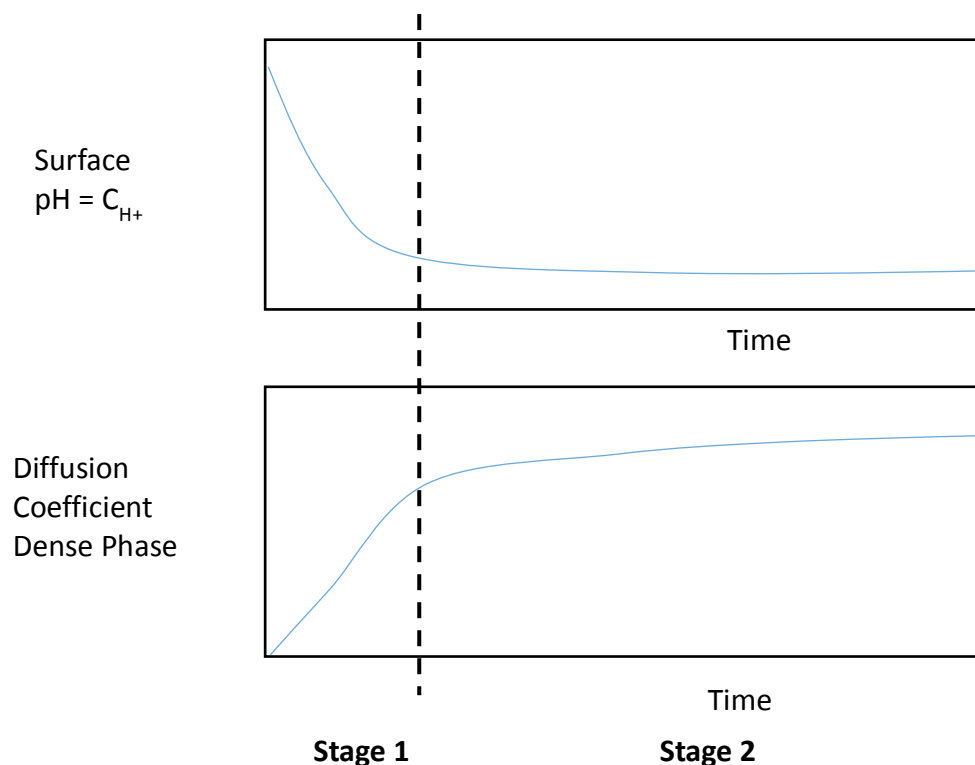


Figure 4. Dependency of Surface pH and acid diffusion coefficient through the coating with time.

Table 3. Acid Permeation, Surface pH and Diffusion Models for Short Term and Long Term Performance of Epoxy Coatings.

Model(s)	Stage 1 (Short term 1-2 years)	Eqn No.	Stage 2 (>3 years)	Eqn No.
Surface pH with time	$C_{H^+} = \frac{1}{C_0} t^\beta$	(1)	$C_{H^+} = \text{constant}$	(2)
Acid Diffusion with time	$D(t) = D_o t^m$	(3)	$D(t) = D_o t^m$	(3)
Diffusion vs Coating Properties and Environmental Conditions	D(t) = fn [environmental conditions, chemical properties of coating, physical properties of coatings)			
Permeation model	$C = 1/C_o \Gamma(\beta + 1) (4t)^\beta i^{2\beta} \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$	(4)	$C = C_{H^+} \operatorname{erfc}\left(\frac{x}{2\sqrt{D(t)t}}\right)$	(5)

Table 4. Nomenclature for Acid Permeation, Surface pH and Diffusion Models

Function	Definition	Units
C_{H^+}	acid concentration calculated from the surface pH ($pH = -\log(C_{H^+})$)	(moles/L)
C_0, β	constant and power of equation (1). These are determined by fitting measured acid concentration(C_{H^+}) with time	1/day, none
D_0, m	constant and power of equation (3). These are determined by fitting measured diffusion coefficient with time	cm ² /s, none
$D(t)$	acid diffusion coefficient as a function of time	cm ² /s
t	time	(days)
x	depth of acid permeation	(cm)
Γ	gamma function	
$\text{erfc}(x)$	complementary error function = $1 - \text{erf}(x)$	
$\text{erf}(x)$	error function = $\frac{2}{\pi} \int_0^x e^{-t^2} dt$	
$i^n \text{erfc}(x)$	iterated integral of the complementary function	
Environmental conditions	H ₂ S (ppm), Temperature (°C), Relative Humidity (%)	
Chemical properties of coating	LOI (loss on ignition, % determined by XRF), filler size (µm), filler (%), hydrophobicity (FTIR: (OH/benzene) peak ratio)	
Physical property of coating	thickness (mm)	

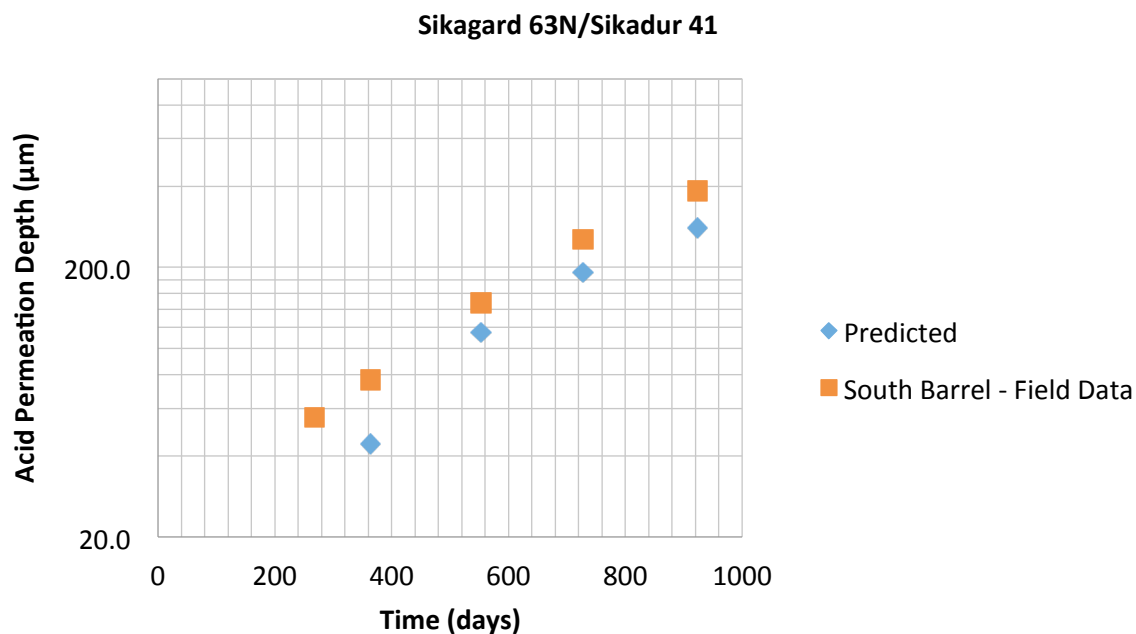


Figure 5. Validation of permeation model over short term service life.

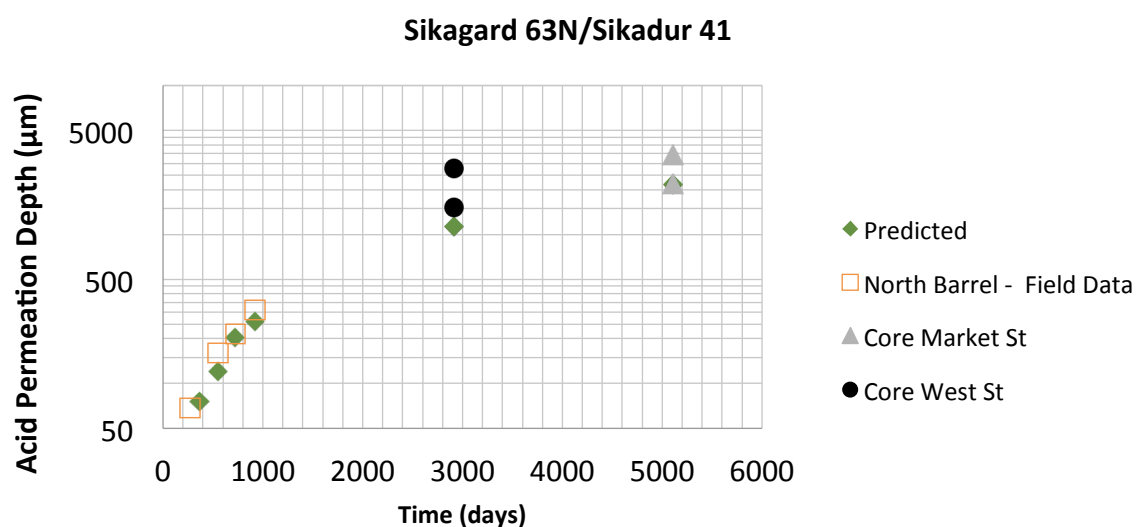


Figure 6. Validation of permeation model over long term service life.

1.3.3 Condition Assessment of Epoxy/Epoxy Mortar Coatings

The following condition assessment strategy has been developed under SP2. Monitoring the performance of epoxy based coating could involve the following characterisations:

SP2 (ARC Sewer Corrosion and Odour Research Project)

- **Acid Permeation**
 - i. Microscopy
- **Chemical Change**
 - i. Surface pH
 - ii. Bulk pH
 - iii. Biogenic acid analysis
 - iv. Hydrophobicity (FTIR)
 - v. Thermal analysis (TGA)
- **Physical Changes**
 - i) Bonding Strength
 - ii) Shrinkage, Expansion
 - iii) Hardness (Shore D Hardness)

1.3.4 Accelerated and Field –Short and Long Term Test

- Accelerated laboratory test involves immersing epoxy in specific acid baths or corroding environment to monitor the acid permeation (ASTM D570-98).
- Short term (1-3 years) and medium to long term (3-15 years) tests are performed by applying the coating directly on sewer walls and periodically examining the acid permeation and the corresponding physical and chemical changes.
- Short term field test with controlled H₂S conditions can also be obtained by installing coupons in the SA Water's Bolivar Chamber in South Australia.

1.4 Cost

No prices of epoxy/epoxy mortar coatings are available.

1.5 Impact on WWTP

- Polymeric coatings show variable performance in the field with service life from 1 year, whilst other coatings continue to perform after 15 years.
- Polymeric coatings that are able to adhere show reasonable degree of performance. In Sydney Water epoxy coating continue to provide adequate protection after 15 years (SW Epoxy Projects, 2009).
- In Melbourne Waters, epoxy coating applied as a thin coating (3, 5 mm) has been shown to perform for over 8-9 years. Earlier trials with high build epoxy and vinyl esters installed in the sewers also showed reasonable performance within the 3 year trial period(Wubben 1999).
- In general, most water utilities have observed that thinner polymer lining (< 5mm) are unable to provide adequate protection in the more aggressive conditions found in Australian sewers today(Wubben. 2008)
- Coatings that fail prematurely (< 2 years) do so by localised delamination.
- After coating application and whilst it is in service, epoxy coating manifest various types of defects including formation of pinholes, blister formation, sagging, bulging, cracking,

SP2 (ARC Sewer Corrosion and Odour Research Project)

partial delamination (*peeling of a partial layer of coating*), full delamination (*peeling of the full layer of coating*), softening and discolouration. The exact effect of all these defects, with the exception of delamination and pinholes, on the coating performance and the remaining service life of the coating is unclear to the water utilities.

1.6 Major Limitations

Effect of Moisture on Epoxy Curing

- The high humidity environment and moisture present on the concrete in sewers can affect the curing of the epoxy coating. Improperly cured epoxy coating will not provide resistance to acid permeation and will demonstrate poor adhesion.
- Figure 7 shows the complex effect of substrate moisture on epoxy bond strength. Low moisture content is required to catalyse the curing reaction, whilst high moisture content can hamper the curing process.

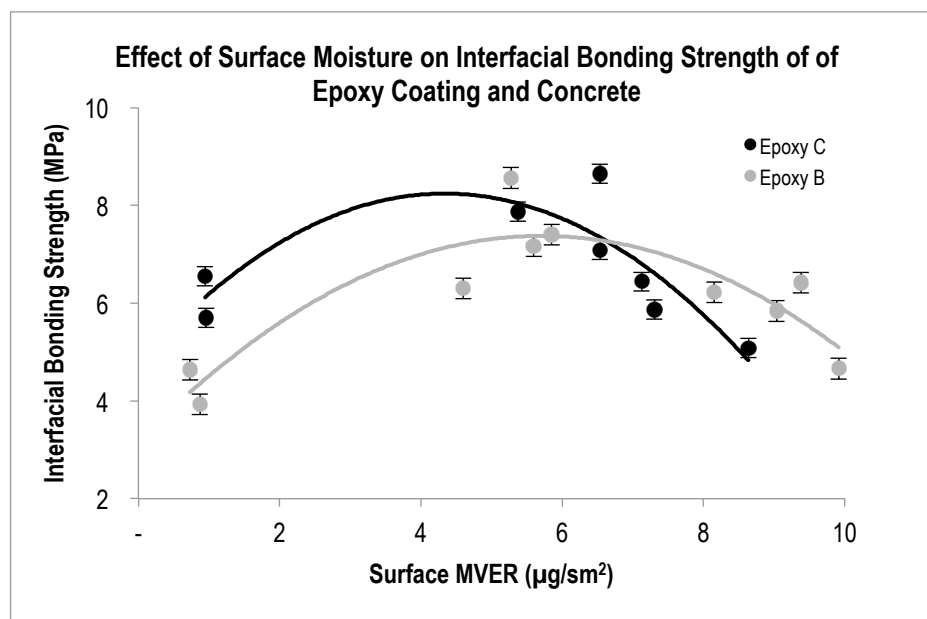


Figure 7. The effect of substrate moisture content (moisture vapour emission rate, MVER) on the bonding strength of epoxy coating.

Infiltration

- The permeation of water from ground water supply through the concrete pipes can build up pressure between the concrete substrate and epoxy. The pressure from the water will often cause the epoxy lining to delaminate.

OHS

- Despite being solventless the epoxy appears to affect the applicators. Some applicators of epoxy coatings suffer from skin disorder when in contact with the coating during application.

Standards used in selecting applicators and the QC/QA of the surface preparation, application, materials, and warranty

- The principle mode of failure of the coating, apart from the natural degradation of the coating, may be introduced by the installation.
- A range of (quality control/ quality assurance) QC/QA clauses are written into the specifications to address this pathway for failure. However it appears there are certain shortfalls in these specifications linked to lack of jurisdictions and structure to implement particular amendments. It may also be linked to the reliance that what may not be specified would be captured in the warranty clause. Specific examples include:
 - i) No accreditation over the training processes for applicators
 - ii) No independent assessment of applicator competency in application and knowledge of the coating system. Although Melbourne Water relies on PCCP (Painting Contractors Certification Program) accredited contractors, who must comply with most of the requirements stipulated in ISO 9001, it is based on quality management rather than technical requirements.
 - iii) QC on surface preparation and application does not integrate the requirements for cleaning and preparing the surface to the needs of the coatings (e.g., moisture content)
 - iv) QC on material (e.g., use of dip card) not in place in some specifications.
 - v) Warranty over long periods (15-50 years) may be difficult to enforce on supplier and applicators.

1.7 Further Information

ARC Linkage Final Report- Field Testing of Epoxy Based Coatings for Sewer Application

1.8 Case Studies

Wubben, R. (1999) Evaluation of Lafarge 'Sewper Mortars' for Aggressive Sewer Environments, ConCorr Pty. Ltd. (submitted to to Lafarge Aluminates).

Wubben., R. (2008). Assessment of Service Life Performance by Core Sampling on Kerneos 'Sewperspray' Application, ConCorr Pty. Ltd. (submitted to Kerneos Aluminate Technologies).

References

1. ASTM (2011). WK33537 Standard to Evaluate High Performance Coatings for Sewer Systems, <http://www.astmnewsroom.org/default.aspx?pageid=2591> (accessed November 30 2011).
2. Wubben, R. (1999). Evaluation of Lafarge 'Sewper Mortars' for Aggressive Sewer Environments, ConCorr Pty. Ltd. (submitted to to Lafarge Aluminates).
3. Wubben., R. (2008). Assessment of Service Life Performance by Core Sampling on Kerneos 'Sewperspray' Application, ConCorr Pty. Ltd. (submitted to Kerneos Aluminate Technologies).
4. AMSS204 (2009). Rehabilitation and corrosion protection of sewers using epoxy coating. Sydney, Sydney Water Corporation.
5. APAS (2003). Specification 214 Coatings for Concrete Used in Sewage Works Australian Paint Approval Scheme.
6. Redner, J. A., Hsi, R.P., Esfandi, E.J., Sydney, R., Jones, R.M., Won, D., Andrraska, J. (2004). Evaluation of Protective Coatings for Concrete. District of Los Angeles, Whittier, California, County Sanitation.