Investigation of the Effect of Water Quality and Lime Dosing on Mild Steel Cement Lined Pipes

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Abstract

Mild steel cement lined (MSCL) pipes are commonly used throughout Western Australia (WA) to deliver water to customers. Over time, calcium hydroxide and calcium from the binder are leached from the cement mortar lining (CML), causing a decrease in the structural integrity of the cement lining within the pipeline and allowing water to reach the mild steel exterior. Additional lime can be dosed into the water to minimise the leaching of calcium hydroxide from the CML, but unnecessary dosing can lead to high operational costs and scaling of pipelines. The relationship between the water quality, lime dosing and CML corrosion level is yet to be fully characterised. This project seeks to develop a model to predict the corrosion level of the CML based on the water quality. This will be done through analysis of water and CML samples taken along existing pipelines around WA. The Calcium Carbonate Precipitate Potential (CCPP) of the water will be calculated using PHREEQC and the CML samples will be analysed using a Scanning Electron Microscope (SEM) and Electron Dispersive Spectroscopy (EDS). As calcium is leached out of the CML, the ratio of calcium to silicon decreases and this will be used to characterise the corrosion level. The corrosion model will be used to help predict dosing requirements and optimum maintenance scheduling.

1. Introduction

The Water Corporation provides customers all over Western Australia with fresh water using a complex network of pipelines, some of which are made of mild steel and are internally cement lined to prevent corrosion due to water-steel contact. One of the issues faced with using cement is that over time corrosive waters can leach out calcium hydroxide and calcium from the binder out of the cement making it more porous. This allows water to reach the mild steel exterior and decreases the strength of the CML. The corrosiveness of the water will affect the amount of calcium hydroxide that could potentially be leached out of the CML, but the relationship between how the water quality affects the corrosion of the CML is still yet to be defined and will be the main focus of this project.

The project will extend over two years, and is currently in its second year. The first year of the project was completed by Kuai (2015) who reviewed various methods of quantifying water quality, developed the basis for a corrosion model, and suggested a sampling plan. The second half of the project includes conducting research into the composition and analysis of CML, collecting water and CML samples, calculation of CCPP values, and using a Scanning Electron Microscope (SEM) to image the CML.

1.1 Water Quality

Potable water contains many trace components that affect its interaction with hardened cement. Studies into methods of quantifying the 'corrosiveness' of water are widely available in literature. Rossum and Merrill (1983) reviewed the main methods including the Langelier Saturation Index, Calcium Carbonate Precipitation Potential (CCPP), Ryznar Index and the Aggressiveness Index. The CCPP was recommended by Rossum and Merrill (1983) and the previous CEED student, Kuai (2015), as it provides a quantitative prediction of the precipitation/dissolution of calcium carbonate. It also takes into account the reaction kinetics involved in the growth of calcium carbonate crystals. A negative CCPP value indicates leaching of calcium hydroxide from the CML, whilst a positive value will result in scaling of the pipeline.

CML consists of aggregates (typically sand) and a binder (Portland cement) that holds the aggregates together. When hydrated, the cement forms portlandite (calcium hydroxide crystals) and calcium-silicate-hydrate (C-S-H) chains (Gaitero, Campillo & Guerrero, 2008). Leaching of calcium hydroxide from the CML occurs when the calcium concentration in the bulk water is lower than the calcium concentration in the pore water. This process is controlled by the diffusion rate of calcium between the two fluids (CSIRO, 2011) and is depicted below in Figure 1. Factors affecting the leaching of calcium hydroxide include exposure to varying water sources, pump-back, temperature, flow rate, and the pipeline age and length. If the water is instead oversaturated with calcium and carbonate ions, then precipitation of calcium carbonate can occur on the water-CML interface, blocking any pores and preventing further leaching from occurring.

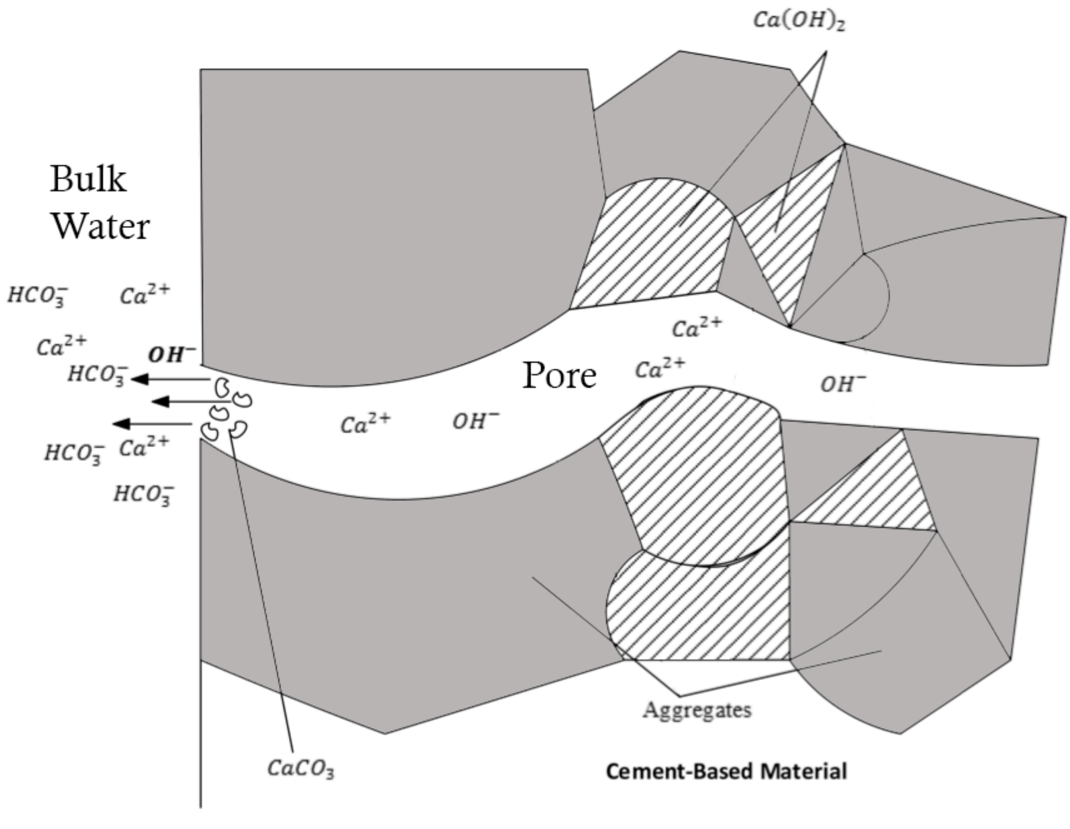

Figure 1. Lime leaching mechanism (adapted from AWWARF (1996)).

1.2 Cement Lining Corrosion

The extent of corrosion of CML can be quantified by its porosity. Porosity will influence the extent to which the CML allows water to seep through to the mild steel, causing corrosion that can lead to possible water bursts. High porosity would also indicate poor structural integrity as there is less binder holding the aggregates together. This can result cement breaking off when exposed to stress.

Cement contains various components. Obtaining a thorough understanding of its structure and composition is crucial in understanding what happens when leaching occurs, and will allow us to identify the features associated with failure. SEM images of a CML sample taken from a southern WA dam is shown below in Figure 2. The large dark grey areas are aggregates, held together by a calcium silicate hydrate binder (lighter grey region). Throughout the binder, there are small white regions that correspond to clusters of calcium hydroxide (Diamond, 2004).

Leaching occurs when the calcium concentration of the cement is higher than that of the water. Calcium can be leached through two main processes, portlandite dissolution or leaching from the calcium-silicate-hydrate (C-S-H) matrix (Ulm, Lemarchand & Heukamp, 2003). It was determined by Ulm, Lemarchand & Heukamp (2003) that when calcium is leached from the portlandite through calcium hydroxide clusters, evident pore spaces are left behind (as indicated in Figure 2 (left)), whilst leaching from the C-S-H matrix does not leave obvious pore spaces but rather results in a 'dissolution front' (as seen in Figure 2 (right)) (Haga et al., 2004). The dissolution front is evident from the loss of colour in the interface between the water and the CML. Calcium atoms contain more protons than silicon and hydrogen, therefore will reflect back more electrons in a SEM and show up brighter in the image. The reduction in calcium hydroxide within the portlandite phase reduces the structural integrity due to the pores left behind. The loss of calcium from the C-S-H phase on the other hand results in a softening of the binder making it less stiff and more elastic (Ulm, Lemarchand & Heukamp, 2003). This would be an issue as the CML would then be more likely to collapse.

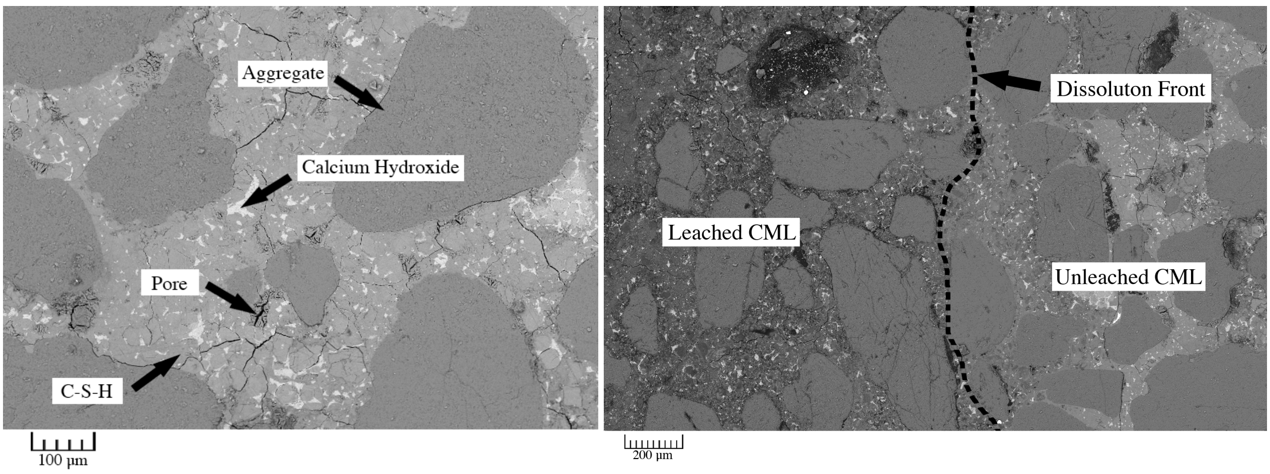

Figure 2. Left: Backscattered electron image of a cross-section of CML (HV: 15 kV, Magnification: 450x, BI: 17). Right: Backscattered electron image showing the dissolution front (HV: 15 kV, Magnification: 200x, BI: 17). Both samples are from a pipeline coming out of a central WA dam.

2. Process

The data for the model is being collected via water sampling, cement lining sampling and analysis using SEM (secondary electron, backscattered electron and EDS). Note that it was difficult to obtain CML samples from pipelines that have experienced consistent conditions over their lifetimes. This was due to pipelines conveying water from changing sources, inconsistent dosing and pump back of water. The need for excavation of buried pipelines also made it difficult to obtain samples.

2.1 Water Characterisation using CCPP

Water samples as well as in-situ temperature and in-situ pH along the length of pipelines around WA are being collected off dedicated tapping points, scour valves or air valves. The samples are then analysed for the following components by SGS Australia:

- Alkalinity (as HCO_3)
- Chloride
- Nitrite and Nitrate
- Calcium
- Magnesium
- Potassium
- Sodium
- Sulfate
- Filterable Reactive Phosphorous

Using the program PHREEQC and the stimela.dat database, the CCPP of the water can be calculated. PHREEQC is a computational program that performs iterative calculations of CCPP until chemical equilibrium is achieved. The stimela.dat database contains the chemical equilibrium constants used in the PHREEQC calculations (de Moel et al., 2013). This will indicate the potential mass of calcium carbonate that can be leached or deposited. For example, the CML sample in Figure 2 was exposed to water with a CCPP value of -18.7 mg/kg H_2O. This means that theoretically, 18.7 mg of calcium carbonate can dissolve from the CML per kilogram of water.

2.2 Cement Analysis

Porosity of cement occurs at a microscale and requires analysis using a scanning electron microscope (SEM). The samples are taken from existing pipelines through hot-tapping, or opportunistically during maintenance and/or shutdowns. The samples are then cut down to a smaller size and vacuum epoxy impregnated to give a smooth surface for analysis. Samples have been collected from Serpentine pipeline, Two Peoples Bay Water Treatment Plant (WTP) and South Dandalup pipeline.

Porosity can be used to determine how much calcium hydroxide has been leached out of the CML and is evident using back-scattered electron imaging. The images can then be analysed using Image J (image analysis software) to determine the percentage pore space. An Energy Dispersive Spectroscopy (EDS) analysis through the thickness of the CML is also being performed on a SEM to provide an elemental composition. Since the decalcification of the C-S-H cannot be identified by pore spaces, EDS analysis would be used instead to identify the decrease in the calcium silicon ratio. A typical unleached CML has an average calcium/silicon molar ratio of 1.7 (Hou, Li & Ma, 2013).

3. Results and Discussion

Four main locations were chosen for analyses so as to primarily avoid excavation and mixed water sources. They include two surface water systems and two groundwater systems. Figure 3 below shows the calculated CCPP of water samples taken along the pipeline of a central WA dam. The results show an overall increase in the CCPP value along the pipeline, indicating that calcium hydroxide is being leached from the CML into the water.

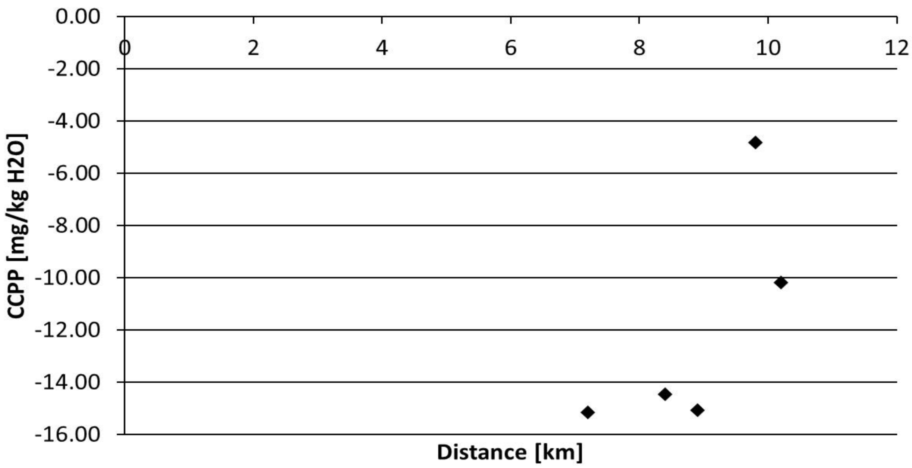

Figure 3. CCPP of surface water along the length of a pipeline located in central WA.

The large rise in CCPP between samples three and four could potentially be due to the mixing of water from a closed off inlet nearby, where the water has a higher retention time. An inspection in 2011 by the Inspection Services Branch (using phenolphthalein sprayed onto the cross section of the CML) showed that the CML for this system had a low level of alkalinity, which is consistent with the predicted leaching from the CCPP values (Water Corporation, 2011). The SEM analysis of CML samples is currently being undertaken.

4. Conclusions and Future Work

The Water Corporation's complex network of pipelines makes it difficult to find an isolated system that conveys single source water with no pump-back (reverse flow of water). Empirical relationships from the data obtained can be tailored specifically for Water Corporation's assets, but they may not be applicable in other locations where the water quality measured lies outside the correlated data. A controlled experimental environment such as a continuous flow loop would be ideal in obtaining better fundamental results. This will allow for the cement lining to be exposed to a constant water quality ensuring that the results *only* correspond to the water quality, and not other factors such as variable cement curing times, exposures to varying water quality over different periods of time and pump-back.

Further work can also be completed on how water quality affects cement-lined tanks. The residence time of water is much longer in tanks than in pipelines, and this may affect the rate at which calcium is leached out due to the stagnant water. The water quality-corrosion model from this project can provide a foundation for predicting the extent of corrosion in cement-lined tanks for a given water quality. Further research and testing would be required to determine how the residence time affects the extent of corrosion. This could be done by measuring the CCPP in the stagnant water at various residence times and correlating it with corrosion level of the CML.

5. Acknowledgements

I would like to extend a huge thanks to my supervisor, client mentors, and everyone at Water Corporation who have welcomed and supported me throughout my project, especially to Tim Ryan, Daniel Minson, Laura Denehy, Murray Wilkinson and Don Kuai. I would also like to thank the staff at CMCA UWA for providing SEM/EDS training and giving me valuable advice on the analysis of my samples.

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