Investigation of Rubber Ring Seal Failures of Water Mains

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Abstract

This project identifies and analyses the mechanisms contributing to the predominant failure mode of the Water Corporation's reinforced concrete water mains. An understanding of rubber seal failures provides a framework to assess the risk of seal failure and an opportunity for proactive renewal. Following previous research that documented the symptoms of ageing in terms of mechanical properties, plastic deformation and material loss, this project focuses on the causes of ageing symptoms and establishes their link with failure conditions. Symptoms of ageing were measured and compared with local failure rates to estimate their relative impacts. Visual comparisons of failed and non-failed seals indicate that the root cause of these seal failures is due to the formation of channels connecting across the pipe-seal interface. Surface hardness, an indicator of the surface crack concentration, correlated strongest with local failure rates.

1. Introduction

The Water Corporation manages over 34000km of the water supply network in Western Australia. Most water mains fail during service and are usually repaired following a failure to minimise water loss. However, undersirable financial costs and customer supply interuptions are associated with these repairs. If the condition of the pipes is judged to be unsatisfactory following a repair, pipe renewal is scheduled to prevent failures that would have occured. An improved understanding of failure modes would assist this judgement. Developing the current understanding of rubber seal failures is the focus of this study, since seal failures appear to be the predominant failure mode of Perth's 3000km of reinforced concrete water mains (Pratt, 2011).

Figure 1 illustrates the characteristic rubber seal failure mode. A seal failure is identified externally by a localised eroded section of pipe barrel adjacent to a leaking joint. Upon disassembly of the joint, a ruptured or dislodged rubber seal is observed. These observations suggest the pipe failure is triggered by a seal allowing water to escape from the water main at high speed. This erodes the external pipe barrel nearby.

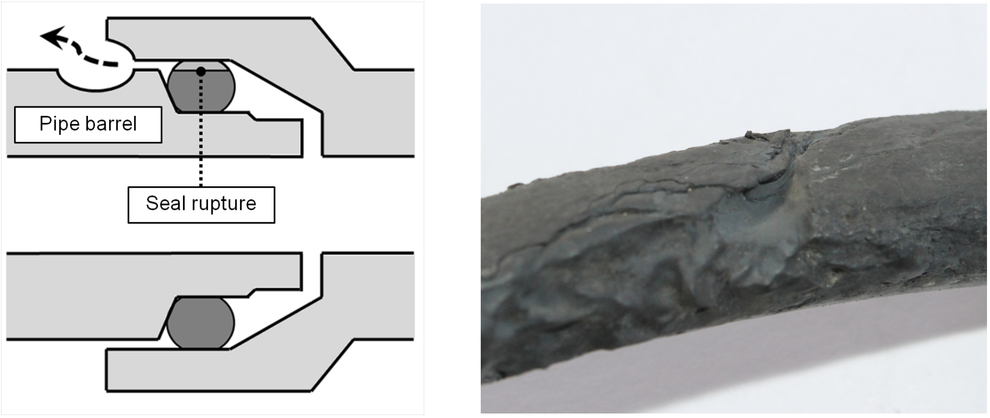

Figure 1 (a) Water jet eroding pipe barrel following seal rupture
(b) Ruptured seal

1.1 Literature Review

Recent research has been conducted by the Water Corporation with a focus on rubber seal failures (Littlechild, 2013). In this study, rubber seals collected from 62 reinforced concrete failure sites in Perth were visually assessed for deterioration mechanisms and were tested for mechanical properties. Stiffness, permanent deformation and material loss were documented and suggested to cause the seal leaks. However, little direct evidence was given to confirm the link between these degradation mechanisms and seal ruptures. Comparisons between the seal mechanical properties with respect to age confirmed stiffness increase with age. The cause behind the seal material loss was left undetermined.

Microbiologic degradation is highlighted as the apparent cause of material loss and failure in several international cases documenting unsatisfactory rubber seal performance in water mains. The issue was first considered possible following proofs showing that microorganisms isolated from soil could consume natural rubber latex (Spence & Van Niel, 1936). This knowledge led to experimental work showing that some specific compositions of vulcanised natural rubber are vulnerable to rubber degrading microorganisms in some soils (Blake, 1949). The first confirmed case of microbiological attack on rubber seals was in the Netherlands. Microorganisms isolated from the soil and water exposed sides of degraded seals in service were shown to be able to consume natural rubber of the same composition as the seals (Rook, 1955). The rate of microbiologic attack was shown to be significant when compared to tests under accelerated conditions using unchlorinated tap water and a degraded seal serving as an inoculator (Leeflang, 1963). Various compositions of natural rubber and synthetic polyisoprene were shown to be vulnerable under the same accelerated conditions; however synthetic rubbers seemed resistant to the microorganisms of this environment (Leeflang, 1963). Similar methodologies were applied to other water main environments and seal types (Hills, 1967) (Kirby & Ridgway, 1982). These led to similar conclusions. According to the Water Corporation's RC water main manufacturer, natural rubber has been exclusively used in their pipes for last 45 years. Microbiologic attack could occur in Perth water mains, provided this natural rubber is vulnerable and the microorganisms are available in high enough numbers on the water or soil exposed sides of the seal.

1.2 Objectives

The aim of this project is to formulate a methodology for assessing the condition of rubber seals to estimate their remaining service life. The pipe or pipe joints can then be scheduled for renewal or large scale repair. The following list of objectives breaks down this project's aim.

1. Determine the causes of rubber seal degradation
2. Determine the impacts of these causes on seal failure
3. Create a decision support tool for seal failure management

2. Methodology

The relative impacts of seal deterioration factors will be determined statistically by linking measured condition values with failure rates. These relationships will be investigated for their feasibility through an understanding of failure modes.

Collection of field seal samples is necessary for experimental testing and condition assessment. Samples are collected opportunistically from leak or burst events associated with rubber seal containing pipes. When a joint failure occurs, a section of pipe containing the failed joint and an adjacent joint is removed. The rubber seals are recovered from the removed pipe section. Seals from 78 failure events in Perth were collected over the span of this project and the previous project (Littlechild, 2013).

2.1 Soil Burial Experiments

The purpose of the soil burial experiments is to determine whether microorganisms are responsible for the observed material loss on the soil side of the collected field samples. A conclusion can be reached through a visual comparison of a field sample surface and a surface known to be degraded by microorganisms created under similar conditions. Identical surface morphologies confirm the theory, while different surface morphologies disprove the theory.

A microbiologically degraded sample is prepared from new natural rubber under accelerated conditions. New natural rubber is obtained from the same seal manufacturer used for RC distribution mains. Three soils are used in this experiment. The first is Rockingham soil collected at about normal pipe depth, the second is market garden soil and the third soil collected was in contact with a degraded section of rubber tyre. The final soil is prepared by mixing the original soil with a nutrient solution containing $MgSO_4$ (0.2g/L), NH_4SO_4 (0.5g/L) and K_2HPO_4 (1g/L) (Spence & Van Niel, 1936) and adjusted to a pH of about 8. The seal pieces are placed in test-tubes and covered in soil. One series of test-tubes are sterilised in an autoclave at 120 degrees C for 5 minutes; the other series is not sterilised. The test-tubes are held at 25 degrees C for a maximum of 2 months. Multiple samples were prepared under the same set of conditions to check progress at various exposure times.

2.2 Seal Condition Assessment

Seals are reviewed visually for clues indicating the seal failure process. Seals that have not failed are visually compared to seals extracted in the early stages of failure.

The extent of material loss and permanent deformation are recorded for each non-ruptured seal collected. Two values representing remaining material loss are taken. One is calculated

from the measured mass accounting for pipe diameter, while the other is the mean thickness between the soil and water exposed surfaces (width). Permanent deformation is measured as the mean thickness between the pipe contact surfaces in the relaxed state (height). Mechanical property parameters obtained from the previous project (Littlechild, 2013) were included as part of the condition assessment.

Historical pipe failure rates (failures/pipe length/time period) were used to distinguish the condition of collected seals. The RC seal failure rates were represented by all RC pipe failures without filtering by failure mode. Each set of seals obtained from an RC pipe failure is matched with a local failure rate. The local failure rate is based on all RC water mains of about the same installation time (±2.5 years) and area (<1km of failure site). Failure data from July 1999 to June 2011 is used. Samples are rejected from analysis if the calculated failure rates are considered unreliable (<9km of RC in area of same age). Relationships are derived by plotting measured parameters against these local failure rates.

3. Results and Discussion

3.1 Soil Burial Experiments

The surface morphologies of the sterilised and non-sterilised samples were compared under SEM. Slight differences were observed after 1 month, but were not significant enough conclude microbiologic degradation had occurred. As a microbiologically degraded surface had not been conclusively obtained, comparisons with a field sample surface are not currently possible. Results after longer exposure times will be published later.

3.2 Seal Failure Cause

Seal material loss is observed exclusively on the surface of the rubber and the extent of material loss varies with location on the rubber surface. On non-failed seals, the greatest material loss is observed on the surfaces exposed to the soil or water sides (Figure 2a). Material loss is almost zero at the pipe-rubber contact surfaces; however upon close inspection, pitting is observed in some localised regions along the seal circumference. Cracking is also observed primarily on the exposed surfaces, indicating that the mechanical properties are weakest at the exposed surfaces and are not uniformly distributed inside the rubber volume. Considering both material loss and mechanical property changes occur in the same regions, the underlying mechanisms could be linked.

The predominant failure mode observed in the rubber seals is rupture, occurring in at least 79% of collected sample sets. Since the mechanical properties are generally weaker at the exposed surfaces, rupture due to surface defects seems more likely than internal defects. However, a brittle surface is not necessary to cause a rupture. Many seals ruptured but did not show clear signs of cracking. Another possibility is the expansion of pits at the pipe-rubber contact, forming a path to allow water escape (Figure 2b). Both these explanations fall under the proposed root cause of connectivity along the pipe-seal contact allowing water to leak out. The channel is then expanded into a larger hole due to post failure material loss.

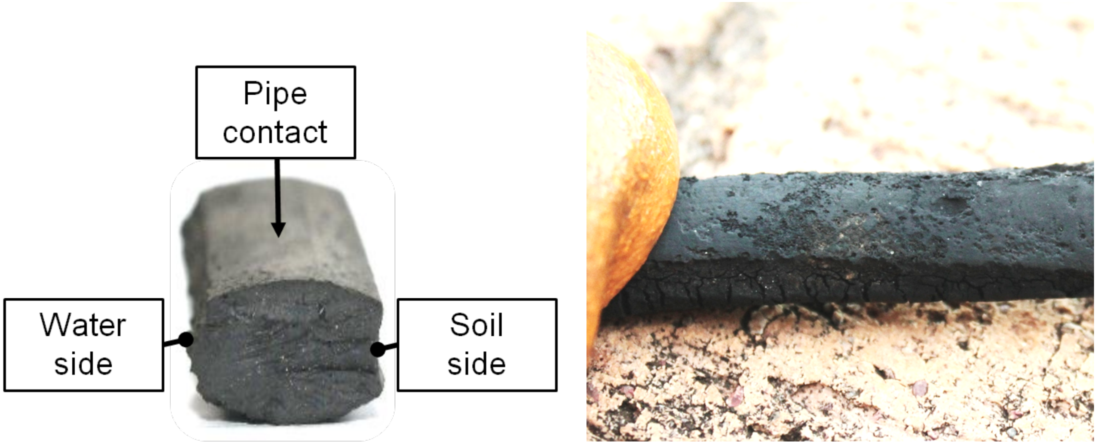

Figure 2 (a) Cross-section of a deteriorated seal
(b) Localised pitting region on non-ruptured seal surface

3.3 Condition Assessment Tools

The relationship between the condition assessment parameters measured and local failure rates are summarised in Table 1. The strongest and most reliable condition assessment parameter measured is surface hardness. A higher surface hardness is associated with a higher failure rate (Figure 3a). This is consistent with the identified failure mode, since a brittle surface is more likely to develop surface cracks and allow water to escape. More material loss is also associated with a higher failure rate; however the accuracy of the current sample pool size is not regarded as high enough to be applied. This inaccuracy is due to filtering, density differences among seals and non-uniform thicknesses. Permanent deformation increased predictably with age; however when taking into account hardness, this parameter did not have any statistical relationship with failure rates.

Parameter	Correlates with age?	Significant?	Accurate?
Age	-	YES	YES
Surface hardness (Shore A)	YES	YES	YES
Material loss (mass)	SLIGHT	SLIGHT	NO
Material loss (width)	SLIGHT	SLIGHT	NO
Permanent deformation (height)	YES	NO	YES

Table 1 Significance to failures and sample data accuracy of condition assessment parameters

The practical value of these relationships is summarised in the steps below for the cost effective pipe renewal based on rubber seal failures.

1. Obtain condition assessment data from the field
2. Obtain local failure rates using Figure 3a, accounting for bias and lagging historical data
3. Obtain the minimum cost function using the calculated failure rate

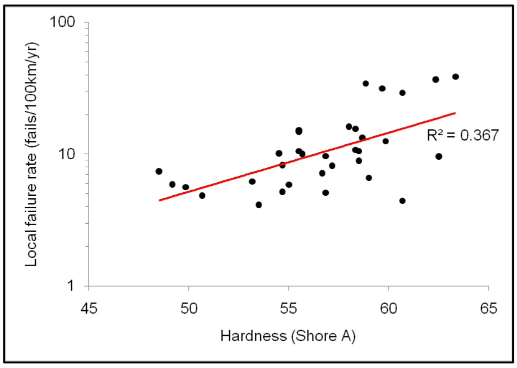

Figure 3 Relationship surface hardness and local failure rates

4. Conclusions and Future Work

The root cause behind rubber seal ruptures documented in WA's reinforced concrete water mains is likely the localised connectivity of defects along the seal-pipe contact. Once a pathway is exposed, water flows through and erodes the rubber and concrete. A condition assessment scale has been developed and could be applied to assist renewals.

The material loss mechanisms on the soil and water exposed surfaces of the seal have not been determined at this time. An investigation into the possibility of microbiologic degradation on the soil side is in progress and will be published later.

Future work should be dedicated to researching methods for cost effective large scale repair of pipe joints and an investigation into measuring the influence of surface porosity on failure probability.

5. References

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