Investigation of Reinforced Concrete Water Main Joint Failures

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Abstract

This project seeks to discover the primary causes of joint failure and to develop tools for the prediction of the failure of joints still in service. These tools will contribute significantly to the creation of an effective asset life cycle management strategy for the remaining reinforced concrete water mains. This will provide more accurate cost forecasting for the Asset Management Branch and will help to reduce the whole of life cost of their assets. Early analysis indicates that the majority of joint failures are caused by the rubber O-ring within the joint failing in its sealing capacity. The possible reasons for the loss of sealing capacity include a loss of elasticity, a loss of profile, rupture or a combination of these mechanisms. All mechanisms are thought to be affected by the ageing behaviour of rubber. As a result the effects of ageing on the mechanical properties of rubber are a focus of this study.

1. Introduction

The three most common materials that Water Corporation uses for its water mains are asbestos cement (AC), polyvinyl chloride (PVC) and steel. Together they account for 74% (by length) of all water mains currently in service. Reinforced Concrete (RC) pipes only represent 8.5% of the Water Corporation's water mains but accounted for 3,128 of 10,980 (29%) of the bursts recorded in the Perth metro region between 2000 and 2008. Steel and AC pipes amounted to only 489 (4.5%) and 2,477 (23%) bursts respectively. There were no burst recorded for PVC pipe in this period. In the 2012 financial year alone there were 644 RC pipe bursts state-wide, which cost the Water Corporation $2.8 million in repairs. Reinforced concrete is presently regarded as an obsolete material for pipes, making way for newer materials. However, the estimated cost of a one-time replacement of the 2,910 km of surviving RC pipes is over $840 million. This imposes a serious challenge to the Asset Management Branch to enact a strategy which balances cost and reliability, particularly with the absence of a reliable knowledge of the service life or failure mechanisms of these pipes to enable prediction of failure.

Work order data from Water Corporation archives suggests that the pipe barrel is the most common failure location. However, a prior investigation found a discrepancy between the recorded failure locations in the work order data and the true failure locations. The work order data observation period spans 12 years from 2000 to 2011. During this time, the majority of bursts (58%) are recorded as having failed at the pipe barrel but many of these bursts were misdiagnosed and failure was in reality attributable to the joint. After consideration of the

misdiagnosis of failures, joints become the most common failure location. This is supported by witness accounts from operators. Furthermore, the 44 samples of RC pipe collected in the previous study had an average condition rating of 1.2 out of 5, indicating that the concrete itself was in very good condition with less than 35% of its service life consumed (Pratt, 2011). It is then postulated that the majority of RC pipe failures are not caused by the deterioration of the concrete but due to the rubber O-ring within the joint failing in its sealing capacity, an example of which is displayed in Figure 1 (a). This allows a high velocity jet of water to escape which rapidly erodes the surrounding concrete and produces a characteristic localised hole pictured in Figure 1 (b).

Figure 1　(a) Failed rubber ring and (b) characteristic RC pipe failure

At present there is no method to pre-detect and prevent RC pipe joint failure, thus the pipes are allowed to operate until failure and then reactive maintenance is performed. The unpredictability of these pipe bursts causes a multitude of problems. If there was a method to help predict RC pipe bursts then scheduled maintenance or replacement could be enacted to lessen the effect of failures.

The objectives of this project are twofold: (1) to ascertain the causes of joint failure of RC pipes and (2) to develop tools for the prediction of joint failure of the pipes still in service. These tools will contribute significantly to the creation of an effective asset life cycle management strategy for the remaining RC water mains. In turn, this will provide more accurate cost forecasting for the Asset Management Branch and will help to reduce the total life cost of their assets.

The failure of the rubber O-rings in their sealing capacity are considered the root cause of the majority of joint failures. The possible reasons for the loss of sealing capacity of an O-ring include loss of elasticity, loss of profile (by material removal or permanent deformation) and rupture. This project conducts the investigation in two parts: (1) statistical analysis of the archive data and (2) experimental investigation to assess the change in physical properties over service time.

2.　Methodology

2.1 Archive Data Analysis

Water Corporation started recording repair work order data for RC pipes in 2000. The 12-year archival data includes information on all pipes and pipe bursts from 2000 to 2011. The data is analysed to identify the frequency of major failure modes of the pipes.

2.2 Experimental Investigation

The sampling strategy is as follows: when operations staff attend a RC pipe burst that has the failure located at the joint they perform the usual repair procedure. This consists of cutting the pipe at the failed joint and then the joint at the other end of that pipe section. If the pipe joint separates easily the rubber O-ring can be extracted by hand, however if the pipe joint is resistant to separation a mallet can be used to knock off the concrete collar to expose the rubber O-ring. This concept was proven with RC pipe samples that remained at the Balcatta depot. The old samples were then disposed of as they were of no further use.

The microstructure of rubber O-rings collected is assessed using Scanning Electron Microscopy (SEM) and Energy Dispersive x-ray Spectroscopy (EDS). Aged samples are compared with new O-rings obtained from the supplier.

Mechanical properties of the aged O-rings are measured with respect to hardness, compression behavior, relaxation behavior and recovery behavior. Hardness is measured using a Shore A Durometer. The behavior of the rubber under compression is measured using an INSTRON material testing machine by recording load and displacement as a sample is compressed to a maximum load. Mechanical relaxation is measured using the INSTRON machine by recording the load and how it changes over time as the sample is held at a fixed displacement. Recovery testing is achieved by comparing the height of samples before and after they have been compressed in a compression set rig for a length of time.

3.　Results and Discussion

3.1 RC Pipe Failure Statistical Analysis

The rate of failure is expected to increase with pipe age but a certain level of unpredictable random failures are also anticipated. There are 32 classes of RC pipe in the Water Corporation database with different nominal diameters. 100 mm pipe (DN100) and 150 mm pipe (DN150) account for 80% (by length) of all RC pipes. Figure 2 shows the burst rate, calculated as number of bursts per 100 km of installed pipe, against pipe age for DN100 and DN150 pipe.
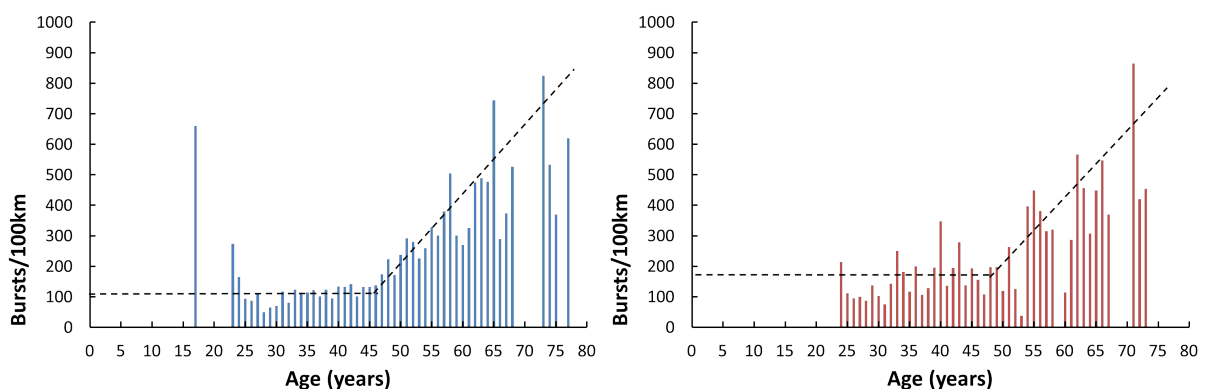

Figure 2　　Burst rate against age for (a) DN100 and (b) DN150 RC pipe

The failure rate appears to remain fairly constant for both graphs until around 45 years when a rapid increase is observed. This could suggest that the effect of ageing becomes significant only after 45 years, at which time the failure rate increases due to the decreased ability of the rubber O-ring to maintain an adequate seal. It is important to note that the observation period for this data only started in 2000 and so records for pipes which have failed prior to 2000 are

likely to be incomplete. There appears to be an anomalous peak in burst rate at the age of 17 years for the DN100 pipe but further inspection of the data revealed that only 151 m of pipe was installed in that year (the average length installed each year was over 28 km).

3.2 Microscopy

Figure 3 shows a SEM image of the surface of a new rubber and of an aged rubber taken at a similar working distance from the test specimen.
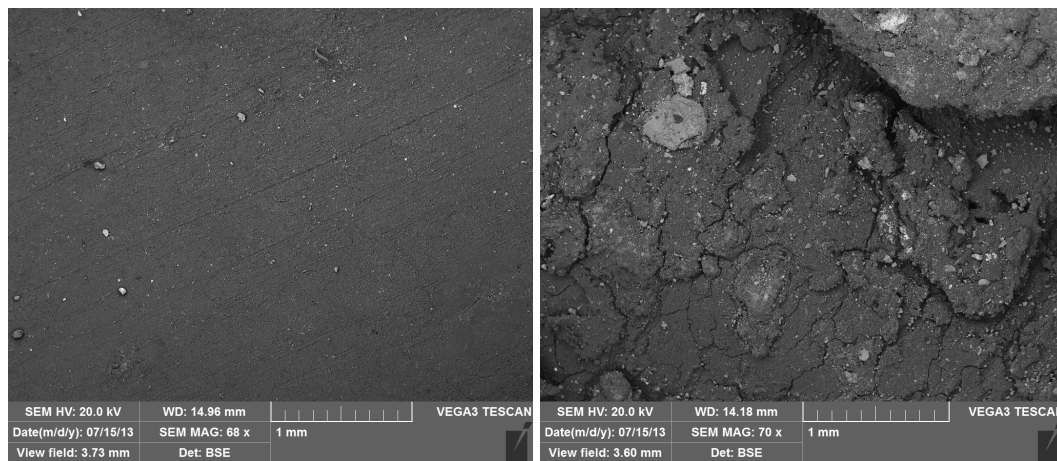

Figure 3   SEM image of surface of (a) new rubber and (b) aged rubber

The new rubber is smooth while the aged rubber is rough with random ridges and valleys. This could be indicative of chemical attack however more testing is required to confirm this.

3.3 Mechanical Testing

The hardness of the rubber is inversely related to its elasticity, the harder the rubber the less elastic (or more stiff and unyielding) it becomes. This will make it more susceptible to failure as the loss of elasticity will reduce the sealing capacity and allow water to escape. The results of hardness testing are displayed in Figure 4 (a). Low strain young's modulus values are found from compression testing and displayed in Figure 4 (b).
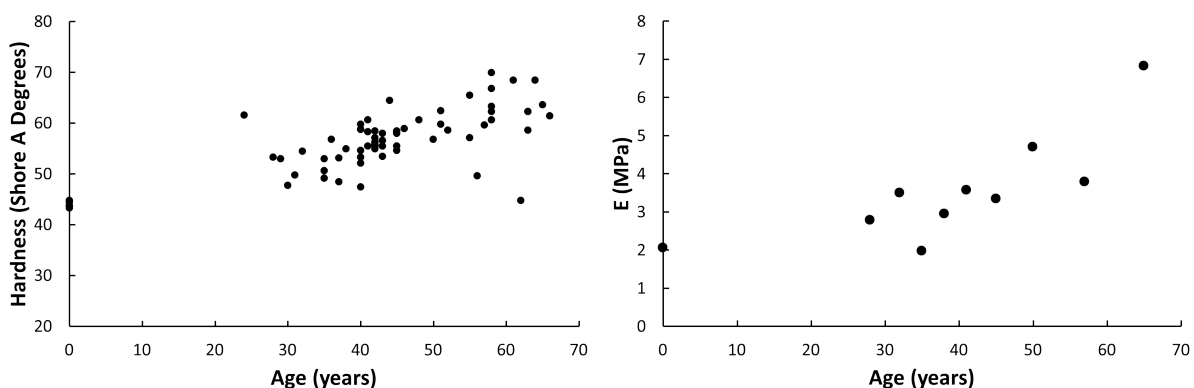

Figure 4   (a) Hardness against age and (b) young's modulus against age

There is a general upwards trend of rubber hardness as age increases, this supports the argument that the rubber O-rings are losing their elasticity. The youngest sample collected is 24 years old and although samples in a new condition were sourced from the supplier there is no data for rubber rings between these two ages. As a result it is not known how the trend

changes in this time, it is possible that there is no change in hardness with age until a critical point or there may be a gradual increase between 0 and 24 years. The young's modulus of the rubber is also seen to follow this upwards trend indicating a stiffening of the rubber, and thus a loss of elasticity, over time.

To further support the argument for a loss of elasticity the compression and relaxation behavior of rubber samples was tested. This involved loading a test specimen up to 0.5 kN on the INSTRON material testing machine and then holding the displacement of the plates constant for 10 minutes to allow the rubber to undergo stress relaxation. Figure 5 shows the load-displacement and load-time graphs for several rubber samples, the vertical lines at the end of the load-displacement curves represent the relaxation of the rubber at a constant displacement which is plotted on the load-time graph to show relaxation behavior.
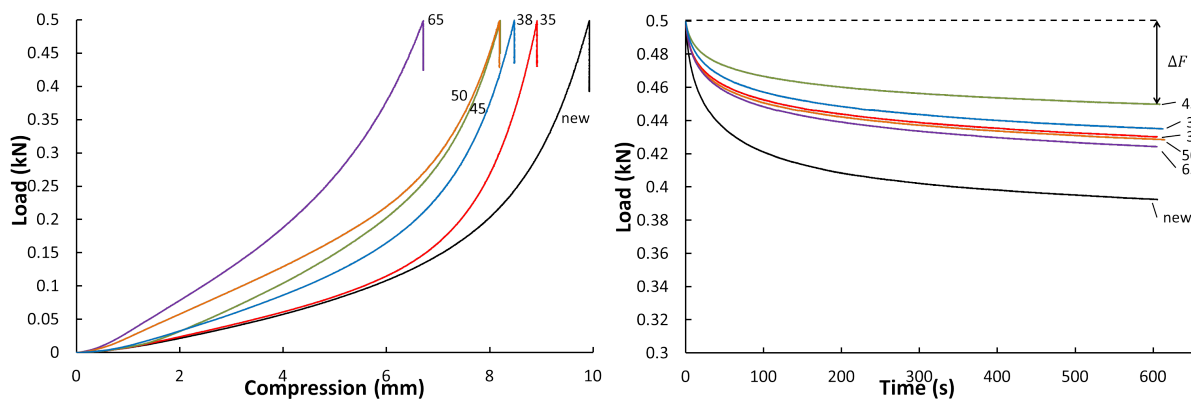

Figure 5   (a) Load-displacement graph and (b) load-time graph

The amount of relaxation is quantified by subtracting the load the rubber relaxes to from the initial load of 0.5 kN. This is referred to as ΔF and is plotted against various ages of rubber in Figure 6 (a). The recovery behavior is shown in Figure 6 (b) and is quantified by ΔL which is the amount of deformation recovered under zero stress after the rubber has been held at a specified compression level in the compression set rig for a given length of time. The data shown in Figure 6 (b) came from samples that were held at ~40% compression for 2 days.
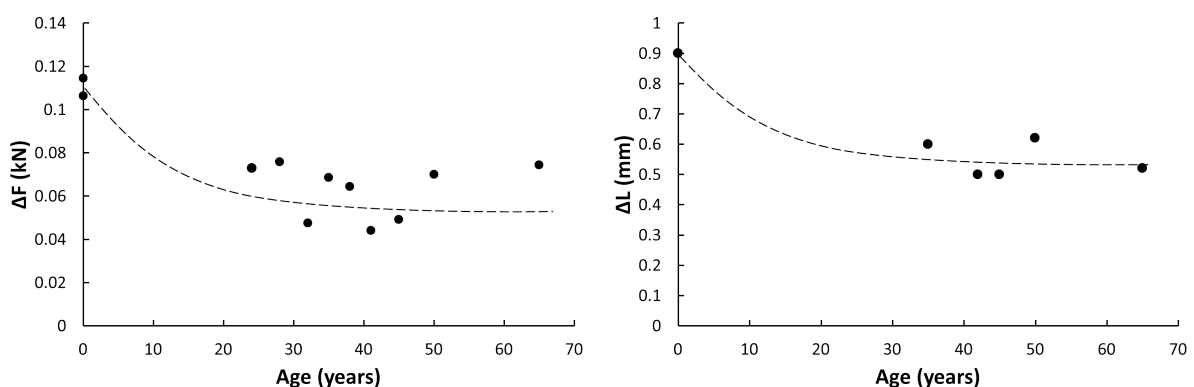

Figure 6   (a) Relaxation behavior and (b) recovery behavior

There is a general downward trend for both graphs which then appears to plateau. Stress relaxation in natural rubber occurs through viscoelastic flow within the material or through scission of the polymer chains or crosslinks (Robinson & Vodden, 1955). The reason for a decreased level of stress relaxation for older samples is that a degree of viscoelastic flow will have already occurred so that under a compression test there is a limit to the amount of further chain-on-chain slippage and untangling of chains. This means less stress can be relieved

through these mechanisms. Similarly less deformation can be recovered as the rubber ages as more crosslinks undergo chain scission leaving fewer strained crosslinks that have the ability of applying a restoring force.

4.　Conclusions and Future Work

Evidence suggests a definite change to the behavior of natural rubber as it ages. The rubber O-rings are seen to harden over time with a gradual upwards trend. This hardening of rubber is indicative of the gradual loss of elasticity the material experiences as time progresses. The loss of elasticity is one suggested cause for an increase in failure rate which could be the reason for the sudden increase in historic failure data observed between 45 and 50 years of pipe age. The other failure modes suggested by this study are a loss of profile and rupture of the rubber. These two failure modes require further analysis so that the most significant of the three failure modes can be identified. Figure 7 shows the cross-section of a rubber that has undergone significant material removal. Loss of profile, specifically material removal, can be a result of the previously described water jet eroding the rubber as it evacuates the pipe. This makes it difficult to classify whether loss of profile is the cause of a pipe burst event or a subsequent consequence of a burst caused by another failure mode. It is suggested that any future work should be focused on the loss of profile through material removal.
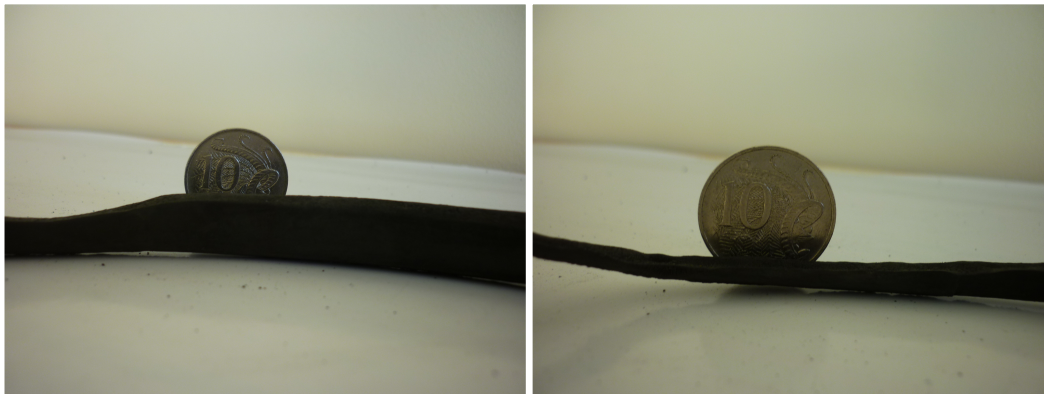

Figure 7　　(a) Rubber O-ring with little to no material removal and (b) rubber O-ring with severe material removal

5.　References

Kirby, P.C. & Ridgway, J.W. (1980) Recent Developments in Rubber Joint Ring for Water Mains, *The use of plastics and rubber in water and effluents*, pp. 6.1-6.15.

Linos, A. & Steinbüchel, A. (2001) Biodegradation of Natural and Synthetic Rubbers. In: A. Steinbüchel, ed. Biopolymers Vol. 2: Polyisoprenoids. Germany: Wiley-VCH.

Pratt, C. (2011) Factors Influencing Pipe Failures in the WA Environment, Perth: The University of Western Australia.

Robinson, H.W.H. & Vodden, H.A. (1955) Stress Relaxation in Rubber, *Industrial and engineering chemistry*, **47** (7) pp. 1477-1481.