Deterioration of Asbestos-Cement Pipes

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Abstract

Asbestos cement (AC) pipes make up 33% of the Water Corporation's total pipe network, mainly reticulation piping. It has been discovered that they are not resistant to corrosion as assumed upon installation and the piping has experienced some deterioration over the past few decades. The entire replacement cost of the AC piping network is estimated to be more than $1B for the existing system managed by Water Corporation. A strategy to minimise the cost is to be able to predict more accurately the condition of the pipes. The condition predicted by the Jarvis model was analysed by evaluating the structure and mechanical properties of AC pipes that have been in service for a number of years. The mechanical properties of a sample of AC pipe were found to differ in their condition predicted by the model used by Water Corporation. Furthermore, micro-structural analysis revealed the pipe condition observed is governed by the fibre-matrix bond and leaching reaction-mechanisms, especially internal water aggressiveness. In addition, evaluation of the Jarvis model reveals the methods used to calculate values for soil and water index are unreliable. Therefore, in order to accurately predict the performance and residual life of the AC pipes, the variables should be accurately predicted and the model should be reassessed, with the primary focus on the influence of water chemistry.

1 Introduction

Asbestos cement pipes were initially installed in 1950's in Western Australia, but discontinued in the late 1980's once the dangers of mining and manufacturing the substance were known. Yet, in parts of the metropolitan and country areas the pipes are still in service. Asbestos fibres are known to be reasonably inert in the environment. However, the cement matrix of the pipe can react with the surrounding soils or dissolve ions into the water (AWWA, 1996). The result is gradual internal and external corrosion of the pipe. Asbestos fibres are released into the water and the pipe loses its strength. Hence, the deterioration of the AC pipes has become a concern for the Water Corporation. The replacement cost for Water Corporation is approximately $120 per meter of failed pipe. With approximately 11300km of AC pipes in service, the cost of replacement with PVC pipes is over $1 billion (Loh, 2008). AC pipes are operated to failure and therefore there is need to study these assets and to be able to forecast pipe performance to enable effective future capital planning.

In a previous investigation, a phenomenological model was developed by Jarvis (Jarvis, 1997). The model expresses the pipe condition in a condition index I, which is dependent on four parameters, as:

$$I = 10 - 0.22W + 0.34S + 0.088A$$

where W is a quantitative measure of water aggressiveness based on AI, S is soil Aggressiveness Index and A is the age of the pipe in years (A = 50 for pipe age > 50 years). AI is the water Aggressiveness Index of the reticulation water flowing through the pipe, and

$$W = 0 \qquad \text{for } AI \geq 12$$
$$W = (600/AI) - 50 \qquad \text{for } 10 < AI < 12$$
$$W = 10 \qquad \text{for } AI \leq 10$$

A condition of I=0 indicates the condition of the pipe is very poor and I=10 reflects a pipe in very good condition.

This project is a continuation of AC pipe study, examining the structure, the deterioration factors and the failure mechanisms of AC pipes. To investigate the limitations of this model, a number of AC pipes were selected and evaluated, as listed in table 1.

Table 1: Pipe sample condition

Sample	Age (year)	S	W	I
DN150 Young	31	3	3.67	5.4
DN150 Mid	42	3	3.67	4.5
DN150 Old	50	3	3.67	3.8
DN150 Failed	31	3	3.67	5.4
DN58 Young	31	3	3.67	5.4
DN100 Young	31	4	3.67	5.1
DN200 Young	31	3	3.67	5.4

2 Experimental methods

The methodology for AC pipe testing was restricted by strict safety guidelines. The experimentation of this project consisted of three parts; visual examination, mechanical tests and microstructure analysis of AC pipes. Visual examination was conducted using 0.01% phenolphthalein to moisten a cut surface of the sample. Sound material is indicated by the violet colour and leached material is colourless, as shown in figure 1.

The mechanical properties were examined through Vickers hardness, compressive and three point bending tests. Compressive test was conducted on an Instron 8501 machine with V-shaped testing blocks as shown in figure 2. The samples were cut by JPJ constructions according to the ratio of 1:1 of diameter to length. Three-point bending test was performed using pre-cut samples of 10x10x150mm rectangular strips. The support distance for the three-point bending was 75mm.

The microstructure of the AC samples was examined by using a Zeiss 1555 (Figure 3) scanning electron microscope (SEM) which was equipped with an energy dispersive spectrometry (EDS) analyser for compositional analysis.

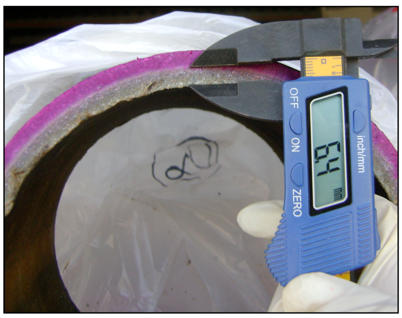

Figure 1: phenolphthalein testing of AC pipe.

Figure 2: Crushing test using the Instron machine with V-blocks.

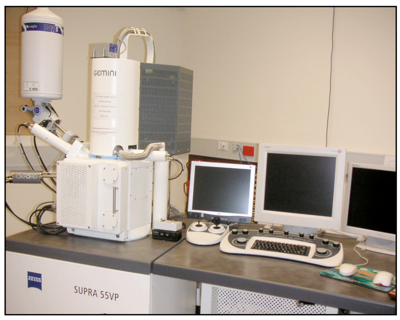

Figure 3: Zeiss 1555 SEM used for structural and EDS analysis.

3 Results

3.1 Visual examination

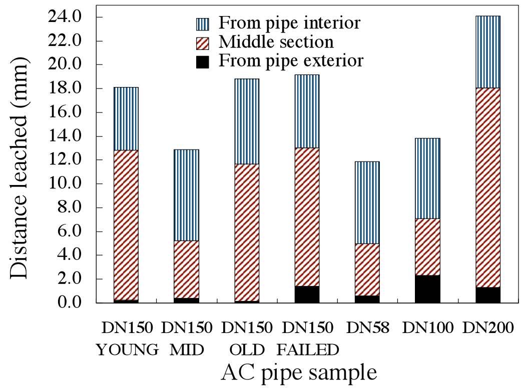

Figure 4: Distance leached in the AC

Figure 4 shows the sections of the pipes that have been affected as determined by the phenolphthalein testing. Minimal deterioration from the pipe exterior was observed in these samples but mainly from the interior of the pipe. It is known when low calcium water (soft water) is in contact with AC pipe, leaching of the calcium silicate and calcium hydroxide from the pipe matrix occurs. A weak shell of silicate and asbestos fibres, with a consistency like paper-maché, is left behind (AWWA 1996). Therefore the amount of material leached out highlights the section of the pipe with effectively no strength. If the measured maximum amount lost from both inside and outside is subtracted from the overall wall thickness the effective wall thickness of the pipe is determined. Therefore it can be deduced that the average effective wall thickness of the pipe is the actual remaining pipe wall holding the reticulation water.

3.2 Mechanical properties

3.2.1 Hardness test

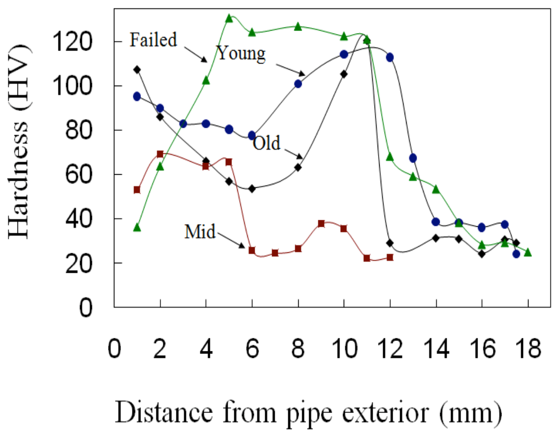

Figure 5: Hardness across the AC

Figure 5 shows the hardness across the pipe cross-section. The higher the HV reading, the harder the material. All the pipes follow a similar trend; the materials have a reasonable hardness reading near the pipe exterior, then increase in material hardness along the cross section till near the interior where the hardness drops to very low values. The large drop in hardness value corresponds to the leached boundary layer noted in the phenolphthalein testing (figure 4). Hence the leaching of the calcium hydroxide and calcium silicate can be correlated to the low hardness value observed near the interior and exterior of the pipe.

3.2.2 Compressive test

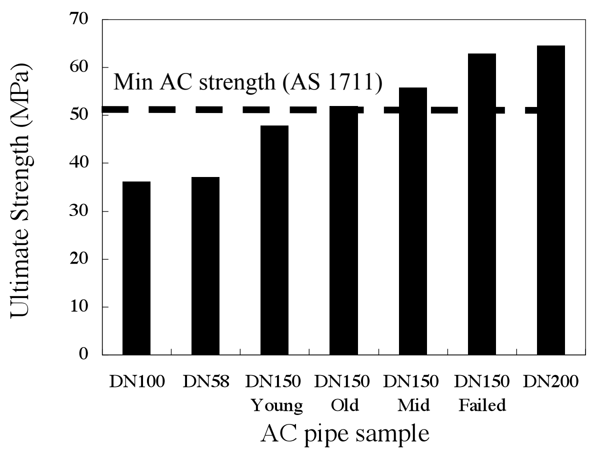

Figure 6: Ultimate strength of AC pipe

Figure 6 reflects the average unit crushing strength of the pipe. The AS1711 classifies the minimum strength required of AC pipes as 51.7MPa. It is visible from the results in figure 6 not all the pipe samples meet this criteria and in fact the older pipe samples have a higher ultimate strength than the younger samples. When the pipe condition predicted by the model was compared with the ultimate strength, a clear correlation with age was not obtained. The model also did not account for pipe diameter and predicted a similar pipe condition for pipes varying in diameter.

However figure 6 show the compressive strength increases with pipe diameter.

3.2.3 Three point bending test

As shown in figure 7 three-point bending test was used to establish if the pipe has sufficient strength to withstand the flexural bending loads experienced in the field. The minimum longitudinal bending strength is defined as 25MPa in the standards. The results are well below these criteria and once again the older pipe samples have a higher ultimate strength than the younger samples. When compared with pipe condition predicted by the Jarvis model, no clear correlation was found between age of the pipe and ultimate tensile stress of the pipe.

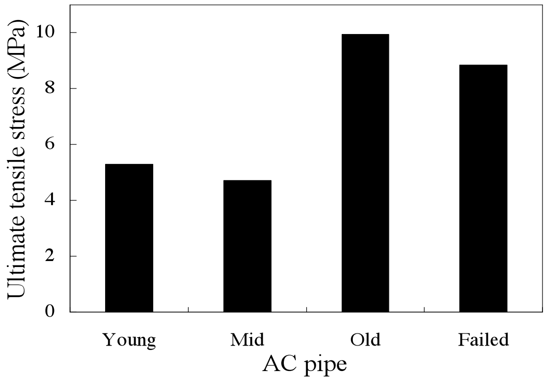

Figure 7: Ultimate tensile stress of AC

3.3 Micro-structural analysis

3.3.1 Scanning Electron Microscopy

Figure 8 illustrates how SEM technology was used to consider the overall structure of the asbestos cement matrix, the shape and arrangement of the fibres and fibre-matrix interface of the AC pipes. Various micrographs were taken at different magnifications form the exterior of the pipe to the interior to study the structural change in pipe along the cross-section.

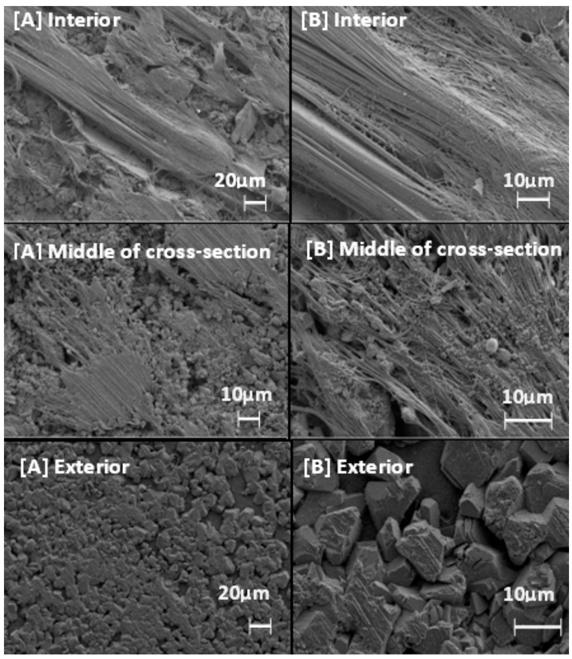

Figure 8: DN150 old sample at a lower magnification (a) and at a higher magnified view (b). Micrographs are taken at 1mm (Exterior), 9.5mm (Middle) and 17mm (Interior) from the pipe exterior, respectively.

The scanning electron microscope images of the AC pipes reflect that the bulk cement matrix does not differ significantly from other cement materials (Bentur et al, 1990). The matrix is made up of asbestos fibres and cement particles ranging in diameter from approximately 1 and 25µm. The micrographs taken indicate that fibres are made up of fibre assemblies, i.e. bundles of monofilaments. Each bundle has a diameter of 60µm or less. The images indicate the fibres have maintained their bundled nature in the composite itself, even after years of natural weathering. Overall near the fibre-matrix interface, it is observed that only the external fibres in the bundle bond to the matrix. It was also observed that fibres obtain uniform fibre distribution and the structure of the fibre-matrix changes with age of the pipe. The micrographs, such as those presented in figure 8, reflected how the cement and fibre composition along the surface vary across the cross-section of the pipe. Near the pipe exterior, more bulk cement matrix is visible. However as we move down the cross section of the pipe, less cement matrix vas visible and more fibres can be seen even at lower magnifications. There is a high possibility in the inner cross-section of the pipe the cement has been leached and with mainly fibres left behind. Fibre-fibre spacing is an important geometrical parameter that controls the performance of the composite (Bentur et al, 1990). Therefore future analysis of fibre-fibre spacing will confirm the variation of mechanical properties.

3.3.2 Energy Dispersive X-ray Analysis:

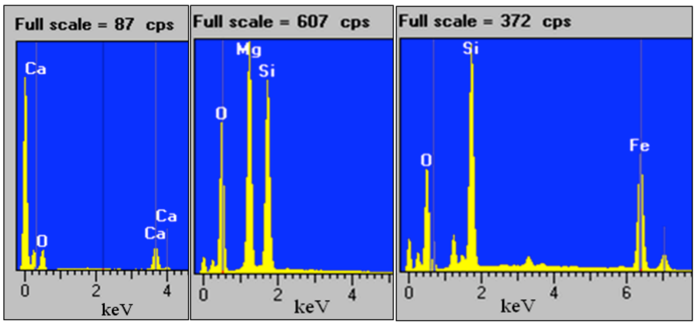

Figure 9: The composition of AC matrix, chrysotile and amosite respectively.

The type of fibres in the pipe will determine its mechanical strength. Additional composition analysis through Energy Dispersive X-ray analysis (EDS) was carried out in order to identify the chemical composition of the fibres within the sample. In the Australian production 85% of the asbestos used were chrysotile (white asbestos) and 15% amosite (brown asbestos), whilst other types of asbestos fibres were not used (Water Authority 1995, Jarvis 1997). Amosite has a chemical composition of $Fe_7[Si_8O_{22}](OH)_2$, whilst white asbestos is composed of $Mg_3Si_2O_5(OH)_4$ (ALS Laboratory Group 2009). Using EDS technique the presence of both asbestos fibres in the WA reticulation and AC pipes was confirmed (figure 9). All asbestos fibre types are mineral silicates, therefore they are classified to have good heat and weathering resistance. However, chrysotile is known to have a higher tensile strength than amosite (ALS Laboratory Group 2009). Hence evaluation of volume fraction of chrysotile and amosite in each sample will show the variance in strength.

4 Discussion

The difference in mechanical properties discovered previously in the samples was primarily due to internal deterioration. The concentration of the chemical components present in the water will determine the level of deterioration and hence the ultimate strength of the AC pipes. There are numerous possible reaction mechanisms affecting the mechanical strength of AC pipe.

Carbonic aggressiveness, i.e. the calcium carbonate saturation state of the water, influences the deterioration of the pipe. When calcium and hydroxide ions diffuse from the pores to the water and carbonate species form the water enter the pores, this results in the formation of calcium carbonate precipitates (AWWA 1996). The deposits will protect the cement material by blocking the transported water from further reacting with the material inside the pores. If calcium carbonate deposit is observed in XRD analysis, this will explain the difference between the mechanical strength in the young and old AC sample.

On the other hand, the younger samples may just be weaker than the older samples due to degradation reactions experienced in those samples. Soft water with low total inorganic carbon also results in the deterioration of the pipe. The inadequate precipitation will result in the cement material degrading as it dissolves.

Other metals such as iron, zinc and manganese present in water also influence rate of deterioration. On the contrary to the chemical components in water influencing the deterioration of AC pipes, these metal ions help slow the rate of deterioration. If a protective coating on the internal pipe surface is applied. This coating inhibits leaching of calcium hydroxide and silicates from the cement matrix.

5 Conclusions and Future Work

5.1 Main conclusions

Pipe condition, I, predicted by the Jarvis model is a reflection of the pipe's strength. However, the model shows no clear correlation with the ultimate strength or flexural strength of pipe samples. The model also failed to show any relation between the leached distance and the predicted condition. However, low hardness values were recorded where leaching was observed from phenolphthalein testing. Hence, SEM analysis of the amount, type and arrangement of fibres in the samples was performed and reflected internal deterioration was the main form of damage observed. Since all the samples are from the same location, Geraldton, the water quality flowing through the pipes can be assumed to be similar. Therefore the main form of reaction mechanism causing internal deterioration is predicted to be carbonation. This is to be confirmed through XRD analysis. In addition, evaluation of the Jarvis model revealed the discrepancy between the model and the results was due to the inaccuracy in the model's variables, S and W. It is recommended a reassessment of the water and soil index and the model be altered to include pipe diameter, as well as a greater influence given to the primary deterioration factor, water chemistry.

5.2 Future research recommendations

X-ray diffraction (XRD) will be used to study the interior of the pipe samples. The technique will allow the composition of the pipe to be determined. In particular, the analysis will focus on the formation (or lack of) of calcium precipitate in pores or the presence of metal ion precipitates formed as a protective coating.

In-depth study of the water chemistry and AC pipe is recommended for future work. The analysis of how the chemical species in the water react with the AC pipes and cause the leaching should be researched further. A prototype for testing accelerated chemical reactions of different types of water, soft or acidic water, is recommended.

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