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Loss of strength in asbestos-cement water pipes due to leaching

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Abstract. Asbestos-cement is a material with valuable strength and durability. It was extensively used for water distribution pipes across the world from the 1950s until the early 1980s. The network of pipes in this case study dates from the 1970s, and after more than 30 to 40 years of service, some pipes have been found to break under common service pressure with no apparent reason. A set of mechanical tests was performed including bending, compression, pressure and crushing tests. Microscopy analysis was also used to understand the material behaviour. Tests showed that there was a clear loss of strength in the pipes and that the safety factor was under the established threshold in most of the specimens. Microscopy results showed morphological damage to the pipes. The loss of strength was attributed to a leaching effect. Leaching damages the cement matrix and reduces the frictional interfacial shear stress.

Keywords: asbestos-cement; failure

1. Introduction

Asbestos fibres mixed with cement were once widely used around the world to produce construction products. The strength and durability of the composite seemed to ensure an everlasting material. Asbestos-cement was used mostly to produce water pipes. Therefore, there are a tremendous number of these asbestos-cement pipes still in service today. Water infrastructure management is economically crucial, see Pelletier *et al.* (2003). But also, the importance of understanding the failure modes of asbestos-cement pipes might help to keep proper pressure at any point in the system, within a range whereby the maximum pressure avoids pipe breakage and the minimum ensures that water is supplied at adequate flow rates for all expected demands.

According to Hu and Hubble (2007), the mechanical failure of pipes falls into one of the following categories: longitudinal cracks, transverse cracks and pinholes. Other failures happen because of singular situations: at joints, bad construction procedures or residual stresses during fabrication.

Longitudinal cracks in pipes are related to pressure that expands the cross section and creates cracks along the pipe. Another common cause of failure is crushing by overload, which can be caused by the weight of soil over the pipe, traffic loads or ice. Transverse cracks happen because of

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bending problems. Normally, imposed displacements are caused by expansive soils; changes in humidity and seasonal weather (rainfalls) may affect the volume of soil and change the support conditions creating flexural stresses; see Hu *et al.* (2008). Pinholes are produced by localised impacts.

In this case study, the network of pipes date from the 1970s. Under normal service pressure, the number of failures has risen continuously during the last five years. All failures modes have been longitudinal cracks. Breaks in the pipe network investigated in this case study were distributed randomly with neither geographical nor geotechnical influence. Seasonal climate changes, including changes in rainfall and some freezing events, could not be responsible for the break pattern of the network. In several cases, traffic loads or maintenance activities might have caused the crushing, but for most of the cases, there were no clear reasons for the failure. We performed a set of experimental tests to characterise the strength capability of the pipes and to try to explain the increase in breaks. An understanding of the problem will drive technical and economic decisions for proper management of these failures.

2. Destructive testing experiments

We obtained 51 specimens from the network that were chosen randomly but distributed such that all areas of territory were explored. All the specimens had the same length, thickness and diameter. We performed 51 failure tests by pressure (Fig. 1), crushing (Fig. 2), and compression (Fig. 3), and we performed 16 additional bending tests (Fig. 4). Pressure, crushing and bending tests followed European Standards EN 512 (1995). Compression tests are not standardised for asbestos-cement pipes, but standards EN 12390-1 (2000) and EN 12390-2 (2000) for concrete aided in the experimental design. Extreme care was taken to ensure a good planar surface between opposite sides, and all specimens were capped with sulphur to reduce the effects of stress concentrations during loading.

The pipes were class C40, i.e., the pipes must resist 40 bars of pressure with stresses below 20 N/mm^2. Results from the pressure tests showed that 9 specimens did not fail (0 stress on the graph).

Fig. 1 Failure of a pressure test

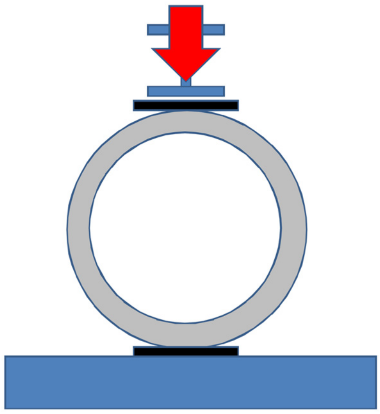

Fig. 2 Crushing test

Fig. 3 Compression test

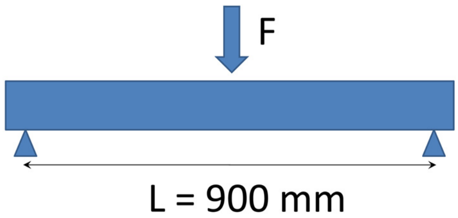

Fig. 4 Bending test

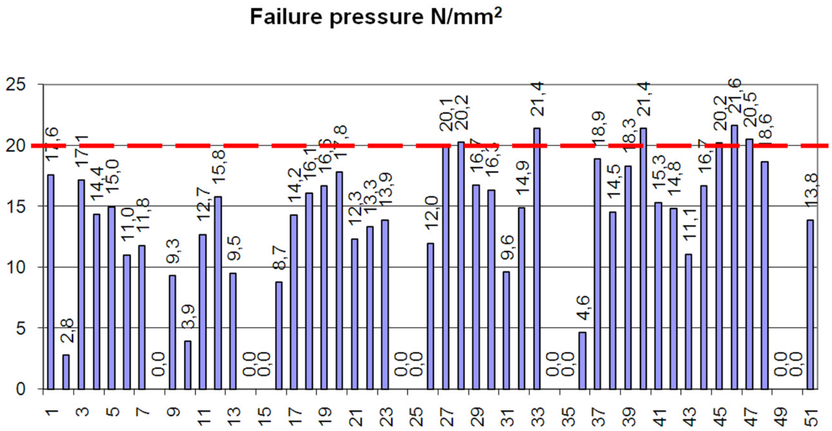

Fig. 5 Bar chart of failure stresses by pressure test

Of the 51 total, 16 pipes still had a safety factor above the value stipulated by the European Standards. However, 68% of the pipes had a safety factor under what was expected for a C40-class material, see Fig. 5.

For the crushing tests, 30 specimens withstood stresses over 45 N/mm^2; therefore, 58% of the pipes had an acceptable safety value for a C40-class material (Fig. 6).

For the bending tests, 63% of the pipes had a safety factor acceptable for a C40-class material (Fig. 7).

For a C40 material, the stress threshold for compression tests is expected to be around 100 N/mm^2 or higher; see Ferrer and Benet (1985). However, all specimens showed very low strength (Fig. 8).

From the destructive experiments performed, it was clear that pipes with low strength could not resist any of the tests. Most of the pipes, after more than 30 years of service, had a safety factor under what is considered acceptable for a C40-class material.

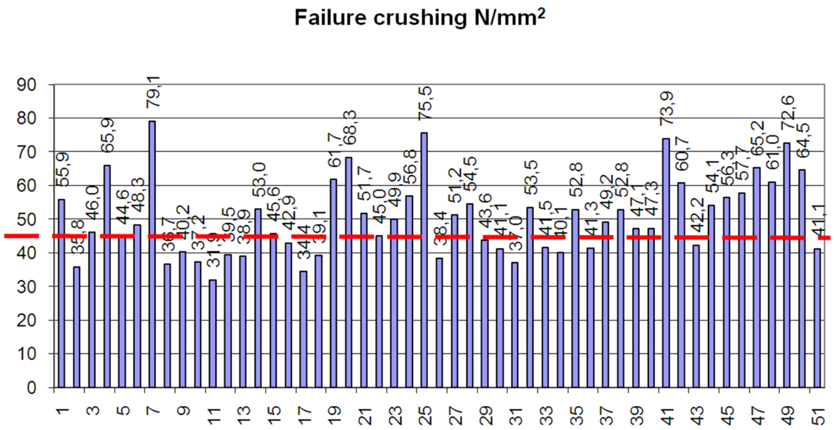

Fig. 6 Bar chart of failure stresses by crushing test

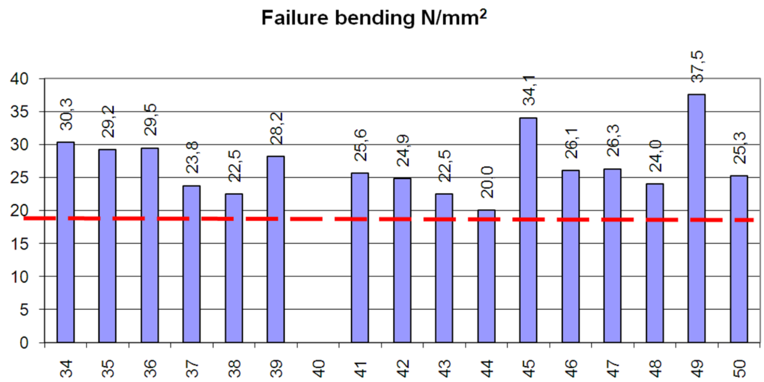

Fig. 7. Bar chart of failure stresses by bending test

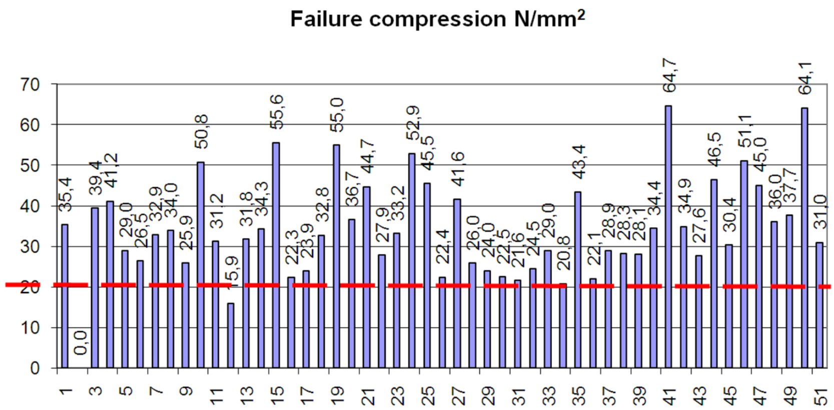

Fig. 8. Bar chart of failure stresses by compression test

3. Microscopy analysis

Microscopy results showed that there was a morphological change among specimens. The healthy pipes had a dark grey colour on the inner and outer side, whereas the weakest pipes had a pale grey colour on the inner side. The inner side of the stronger pipes' surface was uniform and slightly rough, and it was rather difficult to distinguish the fibres from the cement matrix. On the contrary, on the inner side of the weakest pipes, some fibres could be seen separated from the cement with a largely porous and rough surface.

Figs. 9 and 10 show one of the weakest pipes; when compared with Figs. 11 and 12, which show one of the strongest pipes, the differences are clear.

Fig. 9 Microscopy image of pipe's inner surface (weak pipe)

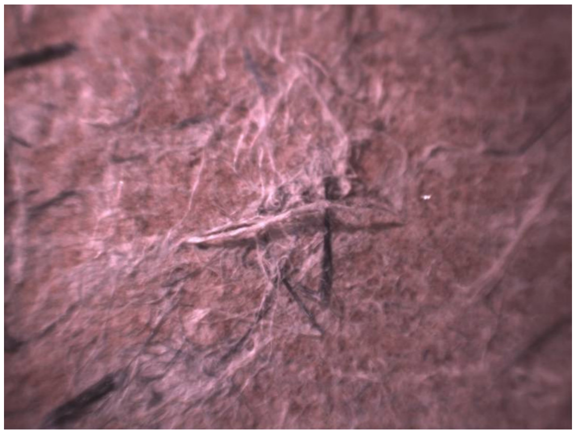

Fig. 10. Microscopy image of pipe's inner surface (weak pipe)

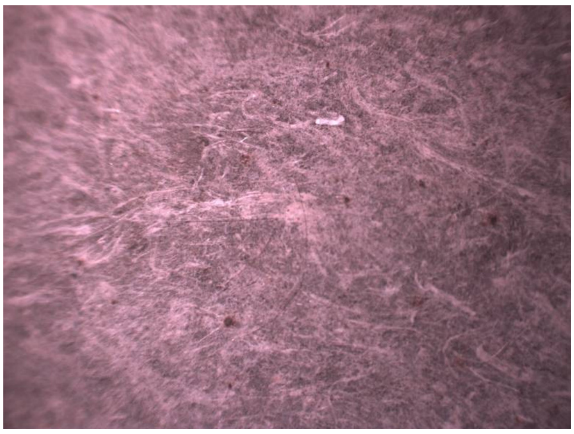

Fig. 11 Microscopy image of pipe's inner surface (strong pipe)

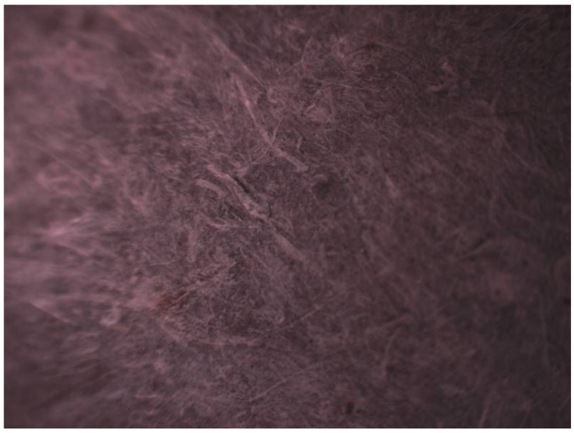

Fig. 12 Microscopy image of pipe's inner surface (strong pipe)

4. Discussion

Microscopy observation showed that most of the specimens, especially the weakest ones, had a rough and porous inner surface and had fibres that were not glued to the cement matrix. On the contrary, the strongest pipes showed a smooth surface on which it was impossible to distinguish fibres from matrix. Moreover, there were colour changes from dark grey on the outer surface of the pipe to pale grey on the inner surface. There is a fuzzy frontier between both colours in the cement paste. Destructive tests showed that many pipes lost strength capability under pressure, crushing and bending. The loss of compressive strength was especially significant for all specimens.

One must take into account that each failure mode induces different collapsing mechanisms. Crushing and bending combine mixed modes of compressive and tensile stresses. Pressure and compression tests produce single stress states: pure tensile and pure compression, respectively. Note that for the compression test, the cement matrix is the material responsible for bearing the external load, and the fibres do not play a relevant role. At a first glance, if the fibres support tensile stresses while the cement matrix supports compressive stresses, the low stresses of the pressure test should be related to the deterioration of the fibres. Nevertheless, in a composite material, the matrix plays an important role in tightening the fibres together and developing a better structural behaviour. Therefore, matrix degradation also contributes to a global reduction in the stress-bearing capacity, and it seems that the loss of strength in the cement matrix could explain the low performance of the specimens for all testing modes.

Another important contribution comes from Akers and Garret's (1983) study of the failure mechanisms of asbestos-cement composites. They performed several bending test, and they monitored the crack propagation and failure of the material. During pressure, crushing and bending tests failure occurred because tensile stresses developed cracks that resulted in the collapse of the specimen. The stress state applied in the current study is comparable to the one developed in the experiments of Akers and Garret. According to Akers and Garret (1983) the development of damage occurs progressively. First, a lot of micro-cracking (less than 1 μm) perpendicular to the tensile stress appears in the cement matrix. Next, cracks start to grow, up to 1-3 μm in width. Hence, fibres start to work in tension and carry loads. The growth of micro cracks mobilises the strength capability of the fibres and relaxes the matrix stress field. These are called main cracks. Some other small cracks grow around the fibres following the load direction and perpendicular to the main cracks. These are the secondary cracks (delamination cracks) that also contribute to the loss of strength of the system. The pulling out of fibres is the main mechanism of failure; nevertheless, fibre failure can also occur.

According to Akers and Garret (1983), the ultimate stress of the material is σ_u:

$$\sigma_u = \eta \, V_f \, \tau \left(\frac{l}{d} \right)$$

where η is the efficiency factor that depends on the fibres' orientation. This factor represents the average distribution of stresses between the matrix and the fibres, and its value depends on the components and distribution. The value of η can be adjusted to $2/\pi$, following Akers and Garret (1983). V_f is the fibre volume fraction (15% for our pipes according URALITA (1966)), and τ is the interfacial shear stress. This stress depends on the strength of the cement matrix, and it is relatively independent of fibre dimensions. Therefore, this value can change dramatically when the cement matrix suffers leaching and loss of strength. An average value could be 2.4 N/mm^2; l is the length

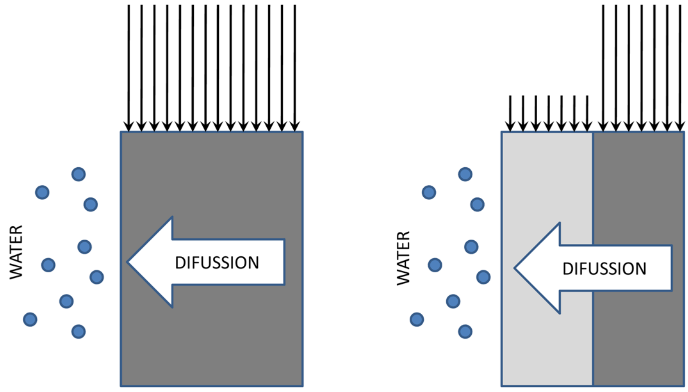

Fig. 13 Leaching mechanism of loss of strength

of the fibres and d is the diameter of the fibres. For our specimens, the factor l/d is around 90 from URALITA (1966).

Hence, it is possible to calculate σ_u :

$$\sigma_u = (2/\pi) \cdot 0.15 \cdot 2.4 \cdot 90 = 20.6 \text{ N/mm}^2$$

This is the expected value for a C40-class material. However, most of the specimens have a lower τ because of the degradation of the cement matrix.

To understand the origin of the degradation of these materials, one must consider that they are in contact with water. Therefore, some authors have contributed the loss of strength of cement materials to leaching effects. In particular, Al-Adeeb *et al.* (1984) have contributed to the understanding of the leaching effects of asbestos-cement. Other authors, such as Mainguy *et al.* (2000), Carde *et al.* (1996); Carde and François (1997, 1999) and Faucon *et al.* (1996), describe chemical attack produced by water on cement pastes and mortars. Water in contact with cement-based materials creates gradients in ionic concentrations that induce diffusion of ions contained in the cement paste. The chemical balance between the paste and the water creates a leaching of portlandite and a progressive decalcification. The dissolution of the cement matrix produces an increase in porosity and a loss of strength (Fig. 13). The effects of porosity on cement pastes are also described by Haga *et al.* (2005).

One of the environmental factors that contribute to the inner deterioration of asbestos-cement pipes is the quality of water; i.e., carbonates and sulphates affect the aggressiveness of the deterioration. Typical indicators of aggressiveness are pH, alkalinity, calcium concentration or sulphate concentration. In particular, the Aggressive Index (AI) and the Langenlier Index (LI) summarise these factors; see AWWA (2003). The latest data from 2011 show that potable water has a pH of 7.8, a Langelier index of 0.14 and an Aggressive index of 12.1. For a pH > 7.0, water is basic; this prevents chemical attacks. When the LI is negative, the water is aggressive; when it is positive, water can form on pipes surfaces, and when it is close to zero, the water is neutral. Finally, for values of AI < 10, water is very aggressive; at values of $10 < \text{AI} < 12$, water is moderately aggressive, and for values of AI > 12, water is considered nonaggressive. In this case study, all indexes are positive but close to boundary values. The calcium hardness was 172.09 mg/L $CaCO_3$, the alkalinity was 115.9 mg/L $CaCO_3$ and the sulphates were 43.2 mg/L SO_4. This means that if there is ever a chemical attack, it would be at a low level and happen slowly; considering the years that these pipes have been in service, a chemical attack may have occurred. In fact, aggressivity of water only accelerates the deterioration. Another point that creates uncertainty is the question of how long the quality of the water has been like it is now. Twenty years ago, the water was surely of lesser quality because it mainly came from water wells and pumps in an industrial region, whereas now it comes from a clean river.

5. Conclusions

Asbestos-cement pipes in service for more than 30 years presented a loss of strength. A set of destructive experiments was performed, testing 51 specimens by compression, bending, crushing and pressure. Compression tests showed weak performance of the material, and the ultimate stress was significantly lower than it what was expected for a standard C40-class material. Tests showed that most of the specimens had a safety factor under the standard threshold.

Microscopy analysis revealed that the material had relevant morphological changes in the inner part of the pipe. Surfaces exposed to the water showed an increase in porosity and roughness, a loss of material, unglued fibres and colour changes. These significant changes could be related to leaching effects in spite of the fact that the water is not currently aggressive. Nevertheless, for long periods of time, the effect of water might create concentration gradients that induce ion diffusion, create porosity and reduce the strength of the material. The loss of strength of the cement paste reduces the interfacial shear stress and the composite material losses its ultimate stress.

This study detected the loss of performance of asbestos-cement composite and found that leaching provides a reasonable explanation for the pipes' failure. Further research should be carried out to prevent failures with non-destructive techniques. The use of ultrasonic waves and impact hammers from the concrete industry could be a good tool to check the cement quality.

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