Inspection of deteriorating asbestos cement force mains with georadar technique
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ABSTRACT
Several breaks on asbestos cement force mains indicated a problem with these kind of force mains. An inspection technique that could give a good idea about the state of asbestos cement pipes was searched for. A georadar technique already existed to inspect drinking water mains and gravity sewers. The technique measures the wall thickness of cement containing materials and it can differentiate between ‘healthy’ and deteriorated material. The technique was applied on four wastewater force mains in Flanders. The results indicated a rapid deterioration of the asbestos cement. A deterioration mechanism called ‘calcium leaching’ was known from asbestos cement drinking water mains. Further it was known that H₂S is produced in force mains and that it can attack concrete containing materials by mains of biogenic sulphuric acid attack. This research checked if both deterioration mechanisms cause the measured rapid deterioration of the asbestos cement force mains. Finally deterioration speeds and minimum required wall thickness were calculated. With the results the residual lifetimes of the force mains were calculated and these could be applied in an asset management program.

Key words | asbestos cement force main, asset management, ATV A127, georadar, residual lifetime

INTRODUCTION
Asbestos cement (AC) used to be a popular building material. It is a strong, fire proof material and easy to work with. A large part of the drinking water distribution network still consists of AC pipes. For wastewater transportation the AC pipes were and still are used as force mains. Although the use of asbestos containing materials is forbidden in Belgium since 2001, existing AC pipes could stay in use. Further, the AC pipes used in wastewater transport pose no direct risks for human health and thus there was no need to replace them.

Aquafin NV is responsible for the financing and implementation of infrastructure for the collection, transport and treatment of the wastewater from the municipalities in Flanders, the north part of Belgium. The last years some incidents with AC force mains were encountered, going from breakages and leaking pipes to the complete disappearing of pipes because of biogenic sulphuric acid corrosion.

Although AC pipes are considered to withstand corrosion, there are three mechanisms of corrosion or deterioration known, causing loss of wall thickness and structural strength.

The first type of deterioration is cavitation. At locations in the force main which reach vacuum pressures, the water vaporizes, creating bubbles. When the pressure rises again, these bubbles implode, creating pressure shocks. These implosions can damage the inside of the pumps and pipes (Hauser 1995). In most force mains preventive measures against high pressure changes were undertaken.

The second degradation mechanism is well known to happen in the gravitational conduits after force mains: H₂S concrete corrosion. However, at high points in the force.

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main profile air is entrapped. At these locations microorganisms transform H$_2$S into sulphuric acid. This sulphuric acid reacts with the calcium ions present in the cement matrix of the pipes to form gypsum (calcium sulphate). This process can quickly diminish the structural strength of the pipe at these locations (Jensen et al. 2008).

The third kind of pipe wall degradation is known as leaching. This mechanism is well studied for AC pipes in the drinking water distribution (Leroy et al. 1996; Mordak & Wheeler 1988; USEPA 2002). The cement salts in the cement matrix hydrate in contact with water and form Ca(OH)$_2$. The latter is leached out of the cement matrix into the water (Buelow & Schock 1981). If the water possesses sufficient acid content, calcium carbonate is dissolved, increasing the water’s hardness, pH, and alkalinity. Because alkaline conditions can’t be maintained in the cement after the initial calcium hydroxide is removed, hydrated calcium silicates convert to more calcium hydroxide. The leaching continues until the water is sufficiently neutralised and the cycle stops. (Leroy et al. 1996). Calcium silicate hydrates are nearly insoluble, but soft waters can progressively hydrolyse them into silica gels, resulting in a soft surface with reduced mechanical strength (USEPA 2002).

The aim of this study was to investigate the deterioration of the pipe wall of AC pipes and based upon the measured residual wall thickness and deterioration speed, to calculate the residual strength and lifetime of the force main.

**MATERIALS AND METHODS**

To determine the condition of an AC force main, two different methods could be applied: (1) the phenolphthalein test is a popular destructive test and (2) the georadar is a non-destructive test. Since the force mains must stay in operation whilst inspecting them, a destructive test was no option. Furthermore, to have an idea of the aggressiveness of the wastewater towards AC pipes, the Langelier Saturation Index was calculated for wastewater samples.

**The georadar technique**

This is a non-destructive technique for assessing the pipe wall condition. The georadar originated from the soil survey sector. The principle of the investigation of AC pipe walls with a radar is based on the delay and reflection of an electromagnetic wave in the wall of the pipes. The difference in time and signal strength between an emitted en reflected impulse is measured. The differences in layer thickness and the varying characteristic electrical properties of the various layers from which the AC pipes are built up, determine the differences in time and signal strength (Figure 1). A high frequency antenna with an intermediate frequency of 1 GHz is used and pushed manually over the external pipe wall. A radar recording is made for every 5 millimetres of the pipe covered. This density yields sufficient information. (Slaats et al. 2004).

The number of inspections on one force main varies with the availability of locations where the force main can be uncovered, the total length of the pipe, and the costs of inspection. The exact and best location of the inspections on the pipe depends on where to expect the most deterioration. Locations with high cavitation probability can be calculated using a hydraulic model of pipe and pumps. H$_2$S corrosion typically occurs where air is entrapped in the pipe or at the outlet. Locations where the highest pressures are expected can also be favoured for inspection.

The inspected locations were typically excavated in a way that the pipe was uncovered for three metres in length and wide enough so that the inspection team could enter the site in a proper way. A lot of care was given to the fact that the pipe at any time was supported by the underlying ground. Usually, a pipe is excavated just until half its diameter.

For small diameters the wall thickness was measured on top of the pipe and on both sides. To estimate the original wall thickness, the circumference was measured.
This measured circumference divided by pi gives the outer diameter, and when the inner diameter is subtracted, it gives an idea of the original wall thickness. For AC pipes the inner diameter always coincides with the nominal diameter. For larger diameter pipes more radar measurements were done between the top and the side of the pipe to get a more detailed view on the spread of deterioration inside the pipe.

At one location the georadar measurement was also combined with a camera-inspection. When it is possible to empty (a part of) the force main, a camera-inspection with radar can be performed over a maximum length of 200 to 300 metres.

Deterioration speed and residual lifetime

A maximum and average deterioration speed of the pipe wall thickness can be determined based on the results of the georadar measurements. The minimum wall thickness, the average wall thickness, the original wall thickness and the pipe age are needed for formula 1 and 2.

\[
v_{\text{max}} = \frac{e_0 - e_{\text{min}}}{t}
\]

(1)

\[
v_{\text{avg}} = \frac{e_0 - e_{\text{avg}}}{t}
\]

(2)

with:

- \(v_{\text{max}}\) maximum deterioration speed [mm/year]
- \(v_{\text{avg}}\) average deterioration speed [mm/year]
- \(e_0\) original wall thickness of pipe [mm]
- \(e_{\text{min}}\) minimum measured wall thickness [mm]
- \(e_{\text{avg}}\) average measured wall thickness [mm]
- \(t\) age of the inspected force main [years]

With the knowledge of the field parameters like ground cover of the pipe, internal pressure, groundwater level, traffic load and construction method, the minimum required wall thickness can be calculated using the German ATV A127 guidelines for static calculation of drains and sewers in the ground (ATV-DVWK-A 127E 2000). The expected residual lifetime of a force main is zero if the measured minimum wall thickness is smaller than the calculated minimum required wall thickness. If this is not the case then the residual lifetime of the force main can be estimated using the following equation:

\[
e_{\text{min}} > e_{\text{req}} \Rightarrow t_{\text{res}} = \frac{e_{\text{min}} - e_{\text{req}}}{v}
\]

(3)

with:

- \(t_{\text{res}}\) residual lifetime of force main [years]
- \(e_{\text{req}}\) required minimum wall thickness [mm]
- \(e_{\text{min}}\) minimum measured wall thickness [mm]
- \(v\) deterioration speed [mm/year]

If for some pipes the minimum measured wall thickness would be smaller or equal to the required minimum wall thickness, then the force mains has no residual lifetime. An optimistic estimation is made by using the average deterioration speed in Equation (3). A minimum residual lifetime is estimated using the maximum deterioration speed in Equation (3). With all these parameters a complete scenario-analysis can be made, estimating optimistic, realistic and pessimistic scenarios.

The Langelier Saturation Index (LSI)

One of the methods to indicate whether the wastewater will have a deteriorating effect on the AC pipes, is to determine the Langelier Saturation Index (LSI). This index indicates the potential aggressiveness of water towards the pipe material. In order to calculate the LSI the following parameters of the wastewater were measured: pH, temperature, alkalinity, total dissolved solids and total hardness. (APHA 1995).

If the value of the LSI is below zero, the water has the potential of being corrosive. If it’s higher than zero, then the water has a scaling potential. (Sawyer et al. 1994; USEPA 2002; Roberge 2006). The LSI is only used as an indication. The calculated values of the LSI of the samples taken at one moment only, don’t tell anything about the conditions of the wastewater in the past or in other circumstances like rainy days. (APHA 1995).

Inspected locations

For this research four pressure pipes at four different locations in Flanders were inspected with the radar technique.
Force main A in Herselt was inspected at three locations. The total length of the force main is 4,320 metres and the diameter is 200 mm. The inspected locations lie at a distance of 1,000, 2,000 and 2,750 metres from the pumping station and are named A1, A2 and A3, respectively. The outlet of this force main was already replaced with HDPE over a distance of 200 metres. Biogenic sulphuric acid corrosion turned the AC wall into a white gypsum wall.

Force main B in Wuustwezel was inspected at two locations to see if it could withstand higher operation pressure in the near future, when a higher flow rate would be applied. The total length of the force main is 1,906 metres and it has a diameter of 350 mm. The inspected locations B1 and B2 are situated at 750 and 1,000 metres from the pumping station, respectively.

Force main C in Berlare was inspected from the inside using a camera combined with radar. Only the outlet part (60 metres) of the force main in the direction of the pumping station was inspected. The force main has a total length of 1,100 metres and a diameter of 250 mm.

Force main D in Brugge was inspected at one location. The force main has a total length of 6,500 metres and a diameter of 900 mm. At six locations this force main crosses an important transportation line, i.e. four big roads and two railways. At these locations an aerator was installed at the highest point. The aerators protect the force main against the water hammer, but they also cause the entrappement of air inside the force main. It is feared that at these locations H₂S deteriorates the walls faster than when only leaching would occur.

At the in- and outlet of the force mains in Brugge, Berlare, Wuustwezel and Herselt wastewater samples were taken to investigate the aggressiveness towards AC, i.e. to calculate the LSI from the measured parameters.

RESULTS AND DISCUSSION

Radar inspection results

The radar technique is a relative new technique in comparison with the phenolphthalein test to measure the ‘healthy’ wall thickness of a force main. In earlier studies measurements with the georadar technique were compared with those of the phenolphthalein test (Slaats & Mesman 2004; Slaats et al. 2004; Mesman & van der Wielen 2005). The general conclusion was that it was difficult to compare both types of measurements at a specific location on the pipe because of the huge difference in technique, but both techniques assessed the inspected pipe in the same condition class.

The radar inspections were performed by an external contractor and results were delivered in graphs with residual strong wall thickness, as is shown in Figure 2. From these results the maximum, minimum and average deterioration speeds were calculated according to Equations (1) and (2). The results are summarised in Table 1.

The maximum deteriorations speeds for force main A are more or less the same for the three locations inspected. With a maximum deterioration speed of 0.29 mm/year this force main ages faster than AC pipes for drinking water distribution. Mordak & Wheeler (1988) reported a maximum deterioration speed of 0.20 mm/year for drinking water AC pipes in the UK. The pipe wall of force main A diminishes rather equally over the total measured pipe length. Considering the fact that no gas was present in the force main at the inspected locations, it was believed that only leaching processes deteriorate the walls of force main A.

Force main B confirmed the results of force main A. The same maximum deterioration speed was found. The average deterioration speed was slightly less than A. Like for force main A the inspected locations didn’t contain any air inside, so it is believed that also here only leaching processes play a role in the deterioration.

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**Figure 2** Results in graph from radar inspection of force main C.
Force main C was inspected over a distance of 60 metres. At a slightly higher point in the profile the deterioration was visibly more severe than in other parts. In Table 1 the deterioration speed of this higher point is given for location C1. It is unknown what causes this faster deterioration. The force main is always completely filled with wastewater from 43 metres from the outlet towards the pumping station. The highest point of the force main lies at 38 metres from the outlet and from this point towards the outlet the wastewater can flow out gravitationally. The boundary at 45 metres where the pipe stays always completely filled with wastewater is also the boundary between the two different deterioration speeds. The boundary was even visible at the images of the camera inspection. It is reasonable to believe that H2S causes a faster deterioration to the part which is exposed to the gasses, but it is unknown why the faster deterioration stops again at 31 metres from the outlet. These differences in deterioration are shown in Figure 2. The deterioration speed for the part that stays always filled with wastewater is given in Table 1 as location C2.

Force main D was inspected only at one location and inspection was hindered by a high groundwater table. The aerator at this location for protection against water hammer provides the sulphide oxidising bacteria with sufficient new air for sulphuric acid production. So, air is always entrapped at this location. This pipe is only 23 years old and already 40% of its original wall thickness has disappeared at this location. Further inspections in the near future have to give a more complete image of the condition of this critical force main.

Leaching potential of the wastewater

All LSI results are given in Table 2. The results of force main A were the most clear. The water entering the force main showed a clear negative LSI, indicating the potential corrosiveness of the wastewater. After 4,320 metres of force main the LSI was still negative, but significantly less than the water that entered the force main.

At force main B there was no possibility to take a sample of the wastewater flowing out of the force main, but the LSI of the wastewater flowing in is clearly negative and has the potential of being corrosive.

The LSI calculated for force main C lies close to zero, being just negative. Only the outlet of the force main was measured with radar, and the measured deterioration here is mostly due to biogenic sulphuric acid attack, i.e. the part of the outlet that runs dry gravitationally and thus where sulphuric acid can be formed. Only the part from a distance of 45 metres towards the pumping station was always completely filled with wastewater. Here the deterioration is due to leaching alone.

The results for force main D give a positive LSI which indicates a scaling potential. The deterioration measured
at this location is supposed to be due to biogenic sulphuric acid attack alone.

**Residual lifetime**

Because of a lack of measurements over time on the same force main, it is unknown how the deterioration speed changes over time. But because a force main of 16 years old, force main A, has a similar deterioration speed as a force main of 50 years old, force main C, it is assumed that the deterioration speed is constant over time.

For force main A the minimum required strong wall thickness was calculated using the German ATV A127E standard. The minimum required wall thickness calculated for force main A was 11.7 mm. The original wall thickness was calculated from the measured circumference of the inspected pipe and was 13.1 mm. The minimum measured strong wall thickness was around 8 mm. This means that although the pipe is only 16 years old, it doesn’t fulfil the requirements of the ATV standard anymore. The residual lifetime is zero years.

Moreover, the total lifetime from the beginning, i.e. the first use of this force main, was only 4.8 years if one would fill in the original wall thickness in stead off the minimum measured wall thickness in formula 3.

The ATV standard uses a safety coefficient of 2.2 for AC pipes. So, the situation becomes really critical when the pipe wall is less than the minimum required strong wall thickness calculated for this pipe without this safety coefficient. With the safety coefficient equal to 1, the minimum required strong wall thickness is 7.7 mm. Only one year is left (= 0.3 mm to deteriorate from the 8 mm minimum measured wall thickness) before the force main enters the critical state where the safety coefficient equals 1.

AC force mains in Flanders were designed without much extra wall thickness for extra safety, and thus, if they loose only a small percentage of their wall thickness, they quickly no longer comply with the design standard. This results in an increasing number of incidents after only a few years of operation.

The residual lifetimes of force mains B, C and D were calculated in a similar way and were 11 years, 0 years and 6 years respectively. The calculations were done with the maximum deterioration speeds and with the minimum measured wall thicknesses.

**Asset management**

With this new knowledge about the possible deterioration speeds of AC force mains, a strategic plan can be made in order to deal with this problem. With a list of all AC force mains, their age and their profile (high points for air entrappement), it is possible to make a prioritization of inspection of these pipes. With the inspection data the residual lifetimes can be calculated and with this information a prioritization list for renovation or replacement can be made.

Old force mains who are already severely deteriorated must be replaced by new ones, but relatively young force mains with still some residual lifetime can be renovated. Applying an epoxy coating on the inside wall of a force main will protect it from further leaching and deterioration. Renovation is much more cost efficient than replacing a force main, since excavating costs can be avoided.

More than AC, ductile iron material with a cement mortar lining is used in Flanders for force mains. What happens with the cement mortar lining of a ductile iron force main? The same leaching process might occur also in these pipes. Once the lining is dissolved, the H2S, which is produced in the biofilm, can attack the iron. According to the most recent ISO 2531 (1991) norm for ductile iron pipes under pressure, new pipes have only a few mm of wall thickness. With the H2S corrosion of steel pipes in mind, this is of major concern and will be topic of further research.

**CONCLUSIONS**

The georadar technique has shown to be a useful tool in estimating the condition of AC force mains. The results of this technique from four inspected force mains, made clear that AC force mains deteriorate faster than AC pipes for drinking water transport.

A maximum deterioration speed without the influence of H2S gas was found to be 0.29 mm/year.
With the influence of H$_2$S the maximum deterioration speed was determined to be 0.73 mm/year.

With this knowledge a prioritization for inspection can be made for AC force mains. Based on the inspection results the residual lifetime can be calculated and a prioritization list for renovation can be made.

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