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ASBESTOS CEMENT WATER MAINS: HISTORY, CURRENT STATE, AND FUTURE PLANNING

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ABSTRACT: About 18% of water distribution pipes in the United States and Canada are constructed of asbestos cement (AC). Aging of AC pipes results in frequent water main breaks. Faced with the potential consequences of water main deterioration and failure, water utilities are in need of comprehensive rehabilitation and replacement strategies for their AC water mains, based on the condition of water mains and forecasts of future failure. This paper reviews available information on AC pipes, especially the manufacturing methods, chemical composition, and the environmental factors that affect the deterioration and failure of AC pipes. It also summarizes current efforts and methods for assessing the conditions of AC pipe and forecasting future performance.

INTRODUCTION

The use of asbestos cement (AC) material for the manufacture of pipes began approximately one hundred years ago in Genoa, Italy. Between 1906 and 1913, a Genoa company combined asbestos fibres with cement to produce a reinforced pipe that would take the high pressure necessary to pump salt water used for street flushing. From this early use, the acceptance of AC pipe for other applications spread rapidly throughout Europe and the rest of the world. It was first introduced in North America in 1929 when Johns-Manville Corporation installed an AC pipe manufacturing machine. AC pipe was a common choice for potable water main construction during 1940s, 50s, and 60s. The use of AC pipe was largely discontinued in North America in the late 1970s due to health concerns associated with the manufacturing process of AC pipes and the possible release of asbestos fibres from deteriorated pipes. However, AC pipe is still a significant portion of the water distribution systems of many cities. It has been estimated that 16 to18% of water distribution pipes in the United States and Canada are asbestos cement. In Regina, Saskatchewan, about two-thirds of the water mains are AC pipes.

AC pipes deteriorate and their breakage frequency increases with age. For instance, during the ten-year period from 1995 to 2004, the City of Regina had an average AC pipe breakage of 0.27 breaks/year/km, which was more than double the average rate of 0.13 breaks/year/km in the period from 1985 to 1994. Faced with increased rates of pipe breakage, high maintenance expenses and possible effects on drinking water quality, most water utilities have developed water main rehabilitation and replacement programs and funded them as part of their annual capital improvement budgets. The goal has been to minimize the high cost of emergency repairs.

Comprehensive management practices are required for water utilities to meet challenges, including public demands for higher levels of service, more stringent water quality and environmental legislation, and increased accountability requirements. The ability to assess and map the present condition of water mains and to forecast future performance is key to the development of a decision-making process.

This paper reviews available AC pipe information, including manufacturing methods, chemical composition, and the environmental factors that affect the deterioration and failure of AC pipes. It summarizes current efforts and methods for assessing present pipe condition and forecasting future pipe performance. These will form the basis for developing management strategies to plan and implement optimal rehabilitation and replacement programs for AC pipes in drinking water distribution systems.

AC PIPE MANUFACTURING

AC pipe properties are closely related to their manufacture process (Figure 1) and chemical composition. AC pipe was made of a mixture of asbestos fibre and Portland cement with or without silica. Portland cement, asbestos, and silica, if any, were proportionally mixed in a vat (j) to form a slurry. The slurry was collected from the vat by a sieve (i) and couche (h) and transferred to a textile felt (f). From the felt, the mixture was collected by a polished metal mandrel (c), the outside diameter being the bore of the pipe. Consolidation of the numerous laminae was effected by line pressure from a hydraulically loaded "beam" (b).

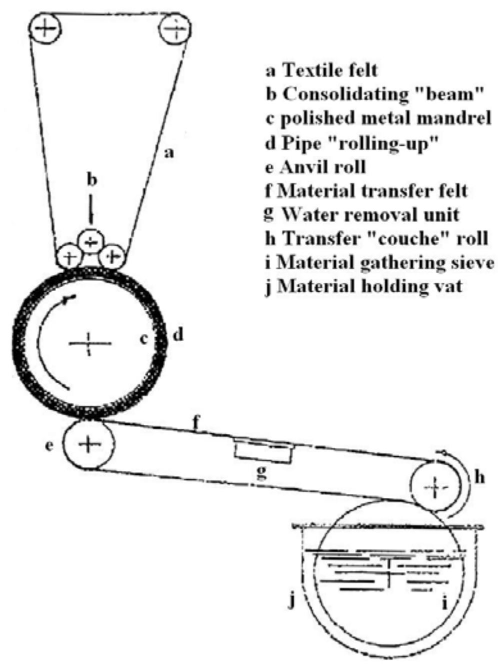

Figure 1. Forming an AC pipe

Once the pipe developed the correct wall thickness, it was removed from the machine and air-matured until it had sufficient handling strength. It was then immersed in water for a prescribed period, usually in excess of 28 days (water curing). AC pipe was also cured in warm saturated air that was below the boiling point of water and at atmospheric pressure (steam curing). The pipe manufactured by either of the curing methods (water or steam curing) is referred to as Type I pipe. Autoclave-cured AC used high pressure steam to cure the pipe by first storing the freshly formed pipe in a moist atmosphere for 24 hr and then treating it in an autoclave operated at pressures between 700 to 1400 kPa (100 to 200 psi) under saturated steam conditions for 16 hr or more (Manson and Blair, 1962). Autoclave-cured AC pipe is referred to as Type II pipe.

CHEMICAL COMPOSITION

Three basic raw materials were used to manufacture AC pipe: asbestos, Portland cement, and silica. Asbestos, about 20% of AC pipe by weight, is a generic name applied to a group of five fibrous silicate minerals: chrysotile, crocidolite, amosite, anthophyllite and tremolite (Nebesar and Riley, 1983). However, only chrysotile and crocidolite (i.e., blue asbestos) were used to manufacture asbestos cement water main pipes. Both types have high strength and sufficient resistance to alkalis and acids, making them essentially inert to chemical attacks in typical water main applications.

Like asbestos, cement is also a generic name, given to complex hydraulic binders, which are a mixture of various oxides and compounds, setting and hardening without disintegration even in water. The main phase compositions in Portland cement are denoted as tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), tetracalcium aluminoferrite (C_4AF), and calcium sulphate ($C\overline{S}$). Of the five types of cements (Types I to V), Types I, II and V were the most prevalent ones used for AC pipe manufacture. Their chemical analyses are shown in Table 1.

When mixed with water, the compounds hydrate, especially the calcium silicates, and this basic reaction causes the cement to set and develop strength. During this hydration process, the calcium silicates go into solution, release calcium hydroxide (free lime), and are precipitated again, chiefly in the form of hydrated monocalcium silicate (tobermorite). The main five components transformed under water-curing conditions are shown in Table 2.

When autoclave-curing was used to manufacture AC pipe, silica replaced up to 40% of the cement. The added silica reacted with the liberated lime to form tobermorite, leaving hardly any free lime. According to Marks and Hutchcroft (1968), free lime in Type I and Type II AC pipe represents 15.5% and 0.4% of the total weight, respectively.

DETERIORTION MECHANISMS

The failure of AC water mains is influenced by a number of factors that can be grouped into three categories: (1) physical characteristics of the pipes (e.g., pipe age, pipe size, manufacturing process); (2) the pipe location environments (e.g., climate, soil type and groundwater properties); and (3) operational characteristics (e.g., conveyed water quality and procedures for operation, maintenance, repair and replacement) (Hu and Hubble, 2007). The interaction of these factors determines the deterioration processes and modes of failure for AC water mains.

Table 1: Typical Analysis of Portland Cement (Bogue, 1955)

Oxide	Amount (%)		
	Type I Ordinary cement	**Type II Moderate sulphate-resisting cement**	**Type V Sulphate-resisting cement**
SiO_2	21.3	22.3	25.0
Al_2O_3	6.0	4.7	3.4
Fe_2O_3	2.7	4.3	2.8
CaO	63.2	63.1	64.1
MgO	2.9	2.5	1.1
SO_3	1.8	1.7	0.9
Potential Phase Composition	**Average Amount (%)**		
C_3S	45	44	38
C_2S	27	31	43
C_3A	11	5	4
C_4AF	8	13	9

Table 2: Cement Hydration (Nebesar and Riley, 1983)

Cement Component	Hydration Product
C_3S, C_2S	Hydrated calcium silicate (tobermorite) gels, $CaO{\cdot}SiO_2{\cdot}3H_2O$ and free lime, $Ca(OH)_2$
$C_3A + Ca(OH)_2$	Hydrated tetracalcium aluminate, $4CaO{\cdot}Al_2O_3{\cdot}12H_2O$
C_4AF	Mixed crystals of hydrated aluminoferrite $(Al_2O_3, Fe_2O_3){\cdot}4CaO{\cdot}12H_2O$
$C\bar{S}$ +aluminate	Hydrated calcium omnosulphoaluminte, $3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O$

Conveyed water quality is one of the most important factors. Asbestos cement, due to its free lime (calcium hydroxide) content, is resistant to alkalis but not to acids. Strong acids are relatively rare in conveyed water; carbonate and sulphate are two main corrosion agents. Soft water with very low ion content (low carbonate and bicarbonate content) is aggressive to calcium hydroxide and results in the leaching of calcium hydroxide from AC pipe materials and a consequent reduction in mechanical strength. Key parameters for identifying aggressive water include low pH, low alkalinity and calcium hardness, as well as negative Langelier index. A negative Langelier index indicates an imbalance between pH, alkalinity and calcium hardness (AwwaRF and DVGW-Technologiezentrum Wasser, 1996).

The factors affecting external chemical attack of AC pipes are similar to those influencing internal attack (i.e., pH, alkalinity and sulphates contained in the soils or groundwater can damage AC pipe materials (Jarvis, 1998)). These chemical processes either leach out components of the cement material or penetrate the pipe wall to form products that weaken the cement matrix, reducing the structural integrity of the pipe as well as affecting water quality.

AC water main failure may also occur as a consequence of mechanical stress on the pipe induced by ground movement of expansive clay soils (Hu and Hubble, 2007). For example, NRC-CSIR researchers installed highly instrumented sections of pipe, including one section of AC pipe, in the expansive soils of Regina to monitor soil and pipe behaviour (Hu and Vu, 2006; Hu *et al.*, 2008). Numerical analysis was performed to study the effect of external environments (such as temperature and precipitation) on soil movement (Vu *et al.*, 2007). The tendency of expansive soils to shrink and swell with changing moisture content can result in differential movement, which causes bending stresses on the pipes or even failure (Hu *et al.,* 2007). A high breakage of AC water mains located in expansive soils was observed during some extreme climate conditions (e.g., Hudak *et al.* (1998) in Texas and Hu and Hubble (2007) in Regina).

Other factors that were reported to have caused failures of AC water mains include operational practices such as water pressure (CH2M HILL, 2001) and maintenance practices such as pipe repair and consequent backfilling (Hu and Hubble, 2007).

CONDITION ASSESSMENT

There are a number of techniques for assessing the condition of pipeline systems. A comprehensive review of the techniques was conducted and summarized in a report by Dorn *et al.* (1996). The techniques that are best suited to AC water mains can be categorized into three groups:

- Performance and physical data assessment: failure record analysis, network modeling;
- Internal environment assessment: calcium carbonate saturation analysis, water quality testing;
- External environment assessment: soil/geological mapping, soil corrosivity mapping, soil tests.

These groups correspond to the factors that contribute to the deterioration and failure of AC water mains. For example, carbonate saturation affects the aggressiveness of the conveyed water and is related to the leaching of calcium hydroxide from internal surfaces of AC pipes. The most important indicators of AC pipe condition are described in the following sections.

Water quality

Langelier index and Aggressive Index (AI, as defined in the AWWA (2003)) are two indexes that are frequently used to indicate whether conveyed water attacks AC pipe and, if so, its degree of aggressiveness. AI is defined, according to AWWA (2003), as follows:

[1] $$AI = pH + \log(A * H)$$

where pH = pH of the water, A = total alkalinity in mg/L as $CaCO_3$ and H = calcium hardness in mg/l as $CaCO_3$. When AI $\leq$ 10, water is considered very aggressive; when 10 < AI < 12, water is considered moderately aggressive; and when AI $\geq$ 12, water is considered non-aggressive.

AI is a modification of the Langelier index (LI), which is defined as (AwwaRF and DVGW-Technologiezentrum Wasser, 1996):

[2] $$LI = pH - pHs$$

where pH is the measured water pH and pHs is the pH at saturation in calcite or calcium carbonate. When LI is negative, the water is aggressive; when LI is positive, the water is non-aggressive and scale can form on pipe interior surfaces; and when LI is close to zero, the water is just saturated with calcium carbonate and will neither be strongly corrosive nor scale forming.

Both AI and LI are indicators of the degree of saturation of calcium carbonate in water and an indication of pH, alkalinity, and calcium concentration. Compared with AI, LI also includes the total dissolved solids and water temperature.

The sulphate concentrations for neutral or basic (pH>7.0) soluble sulphates in water that may affect the condition of AC pipe are shown in Table 3 (AWWA, 2003):

Table 3: Sulphate aggressiveness in water (AWWA, 2003)

Sulphate Aggressiveness Classification	Water-Soluble Sulphates, mg/L SO_4
Non-aggressive	150 and less
Mildly aggressive	150 - 1,500
Moderately aggressive	1,500 - 10,000
Highly aggressive	10,000 and greater

Soil corrosion

The aggressiveness of soils is defined in terms of soil pH and the amount of sulphate present. Table 4 lists the soil pH for non-sulphate acidic soils below which AC pipe will be attacked and the sulphate aggressiveness classification for neutral or basic soluble sulphates in soils according to AWWA (2003).

Table 4: Soil aggressiveness (AWWA, 2003)

	Pipe type	
	Type I	Type II

Non-sulphate acidic soils (pH)	Essentially quiescent	5.0	4.0
	Mildly fluctuating	5.5	5.0
	Rapidly moving or grossly cyclic	6.3	5.5
Neutral (pH=7.0) or basic (pH>7.0) soluble sulphates (mg/L SO_4)	Non-aggressive	1,000 and less	No attack
	Mildly aggressive	1,000-2,000	
	Moderately aggressive	2,000-20,000	
	Highly aggressive	20,000 and greater	

Where the pH of an acidic soluble sulphate is below 7.0 in water and soils, AWWA (2003) provides no guidelines. Tests by Matti and Al-Adeebt (1985) concluded that AC pipes are vulnerable to sulphate attack under this condition and vulnerability depends on the free lime content, the type of cement used, and the permeability and density of the matrix. Type I pipe (high free lime) is most vulnerable to sulphate attack whereas Type II pipe (low free lime) or pipe manufactured from Type II or V cement has more resistance to moderate amounts of sulphates in the soil.

Conroy *et al*. (2005) quantified the effect of conveyed water quality on pipe deterioration by using different linear models to find the best fit between the extent of AC pipe deterioration and some of the factors affecting it. Age, pH and alkalinity were found to be the most significant factors. The best linear fit was

[3] $$\text{Deterioration} = 0.019*\text{age} - 0.365*\text{pH} - 0.003*\text{alkalinity} + 3.26$$

A measure of soil aggressiveness was provided by a quantitative model proposed by Jarvis (1997). In this model, the condition of AC pipe was modelled according to the following equation:

[4] $$\text{Condition} = 10 - (0.088*\text{age} + 0.22*W + 0.34*S)$$

where S is the soil aggressiveness index, and W is the quantitative measure of water aggressiveness based on AI ($W = 0$, for $AI \geq 12$; $W = (600/AI) - 50$, for $10 < AI < 12$; and $W = 10$, for $AI \leq 10$). The model rates pipe condition between 0 (very poor) and 10 where 0 (very good).

Pipe sampling

Pipe sampling provides a means for determining pipe deterioration. It involves removing sample sections of pipes from a distribution system and examining or testing the pipe samples for deterioration. The inspection may be visual observation, scratch tests, Barcol hardness tests, phenolphthalein tests, element analysis, and mechanical tests such as crush/hydrostatic/bending tests in accordance with C500-98 (ASTM, 1998) or splitting compression tests in accordance with C-496 (ASTM, 2004; De Silva *et. al.*, 2002).

Visual observation can be used to identify gross defects/cracks and the general condition of the sample. The inspection is generally used for a gross preview of the sample and is qualitative in nature.

Buelow *et al*. (1980) described a fingernail scratch test for evaluating the softening of the AC pipe interior. The procedure consists simply of determining whether a pipe surface can be scratched with a fingernail. New AC pipe cannot be scratched with a fingernail, but a severely attacked piece of pipe can be scratched easily. A metal scraper has also been used for scratch tests (AwwaRF and DVGW-Technologiezentrum Wasser, 1996). Although a fingernail/metal scratch test is useful for the tentative identification of pipe conditions in the field, this measure cannot quantify the degree of attack for comparison with another section of AC pipe.

Barcol hardness tests that have been used for assessing AC pipe condition include Rockwell "L" hardness measurements and modified Shore "D" durometer readings (Millette *et al*., 1984). Laboratory tests indicated that the hardness measurements and the durometer readings were related to the depth to which calcium had been lost from a pipe exposed to aggressive water, when compared with the results from a scanning electron microscope. The modified durometer test showed promise as a field instrument for determining the deterioration extent of AC pipe.

The phenolphthalein test is a technique particularly suitable for assessing the condition of cementitious materials like asbestos cement (AwwaRF and DVGW-Technologiezentrum Wasser, 1996; Conroy *et al*., 2005). This chemical turns pink in contact with alkali (lime) but remains colourless where lime leaching has occurred. The loss of lime is associated with degradation of the cement structure and indicates the extent of wall thickness that has softened.

Elemental analysis has also been used to determine the extent of AC pipe deterioration by analyzing the elemental composition of the pipe material as a function of the distance from the inner surface of the pipe. Elemental analysis shows a decrease of calcium content in the part of the pipe wall where lime has leached, whereas a general constant percentage of calcium content is indicated in the rest of pipe wall where no degradation has occurred. Analysis of the chemical composition of the undegraded part of the pipe may also indicate the pipe type (Type I or II) or the presence of pipe sections of different manufacturing processes. Both the phenolphthalein test and the elemental analysis can indicate the depth of lime depletion.

Pipe is designed with wall thickness capable of withstanding standard internal pressure and external loading. As pipe degrades, the load bearing capability of the pipe decreases because the degraded part of pipe wall is much weaker than the intact portions (Conroy *et al*., 2005). Therefore, a pipe strength test is an indication of the residual resistance strength of degraded pipe. The residual resistance strength can then be compared with corresponding standards (e.g., AWWA (2003)) or with the current loading conditions (water pressure and external loadings) to calculate the residual safety factor.

Non-destructive testing
The development of remote field eddy current technology, magnetic flux leakage technology, and other new technologies has introduced the possibility of non-destructively assessing the condition of metallic water mains before structural failures occur. For non-metallic pipe such as AC, acoustic assessment technologies for pipe thickness as well as leak location are under development (Hunaidi, 2006).

Another recent development is the use of the Georadar technique to determine the degree of deterioration of AC pipe (Slaats *et al*., 2004). It is based on the different time and strength characteristics of a reflected electromagnetic signal when an impulse travels through deteriorated and intact samples. The results of measurements obtained using the Georadar technique have been compared with results from the phenolphthalein test on pipe segments from the same AC pipes and comparable results were obtained, confirming that the technique is a suitable, non-destructive method for determining the degree of AC pipe deterioration. Although water mains do have to be uncovered to use this technique, there is no interruption to water delivery.

Historical failure data analysis
Water distribution systems may be comprised of hundreds and even thousands of buried pipes, and direct inspection of all of them is often prohibitively expensive. Identifying pipe breakage patterns is an effective and inexpensive alternative to measuring the deterioration of a water distribution system. Various physical and statistical models have been developed to assess pipe conditions based on pipe break data. A comprehensive review of the models was conducted by Kleiner and Rajani (Kleiner and Rajani (2001); Rajani and Kleiner (2001a)). They also developed a multi-variate exponential model to simulate various dynamic or time-dependent factors contributing to water main breaks and to predict water main breaks based on historical break data (Kleiner and Rajani, 2002). The statistical model and a software tool based on the model were successfully applied to both metal (Rajani and Kleiner, 2001b) and AC pipes (Hu and Hubble, 2007; Hu, 2007).

REMAINING LIFE PREDICTION
Pipe condition assessment can indicate only the current condition of AC pipes. A sound management strategy should consider the expected future performance based on remaining service life. Because the deterioration processes and the eventual failure mode of a pipe are influenced by several factors, modeling the remaining life is quite complex. The factors affect not only the deterioration rate, but also the structural resistance capacity of a pipe, two critical components in determining the remaining service life of the pipe (Rajani and Makar, 2000). As indicated in previous sections, the pipe condition can be directly expressed in terms of the lime depletion depth. Therefore, in order to develop a predictive remaining service life model, it is necessary to determine the likely rates of lime depletion when AC pipe is exposed to specific conditions.

Conroy *et al*. (2005) studied the condition of 29 pipe samples and the corresponding age, soil pH and water quality (pH and alkalinity), and correlated the lime depletion rates of the pipes with the corrosive parameters. Different depletion rates were obtained for different soil and conveying water conditions as listed in Table 5.

Table 5: Deterioration Rates for AC Pipe (Conroy *et al.*, 2005)

	Rate of degradation (mm/year)			
	Internal		External	
	Mean	Max	Mean	Max
Soil pH < 7	-	-	0.1	0.27
Soil pH > 7	-	-	0.0	0.0
Soil sulphate class 1*	-	-	0.0	0.0
Soil sulphate class 2 – 5*	-	-	0.1	0.27
Conveyed water pH < 7	0.1	0.27	-	-
Conveyed water pH > 7	0.0	0.0	-	-
Water bicarbonate alkalinity < 55 mg/L	0.02	0.18	-	-
Water bicarbonate alkalinity > 55 mg/L	0.03	0.09	-	-

* Soil is categorized as Class 2 or higher when it has a concentration of >1.2 g/L sulphate (SO_4) using a 2:1 water to soil extract.

It should be noted that the lime depletion rates are imprecise because of the considerable uncertainty involved in deriving the rates. It is recommended that only one of the internal and one of the external factors should be considered, but that the worst case and maximum rates, although conservative, should be used if both of the internal and/or external factors are present.

Davis *et al.* (2005) used another type of deterioration rate model to forecast future pipe condition. In this empirical model, the decrease in tensile strength is used to represent time-dependent degradation due to corrosion, without accounting for the details of the degradation process. The rate of decrease in tensile strength, $d\sigma_t$, is assumed to be constant and can be estimated as

[5] $$d\sigma_t = \frac{\sigma_t - \sigma_0}{Age}$$

where σ_t and σ_0 are the currently measured and the original tensile strengths, respectively. In the absence of experimental data, it is recommended that the minimum tensile requirement specified by some of the standards such as AS 1711 (AS, 1975) be adopted for σ_0 and σ_t can be obtained from mechanical tests on pipe samples such as tensile tests, crush tests, hydrostatic tests and bending tests. The residual strength, combined with the deterioration rates (Table 5 or Eq. (5)), can be used to forecast the strength in the future and the time when the future residual strength passes the corresponding minimum requirements stipulated in standards or other criteria. In this way, the remaining service life can be determined.

CONCLUSIONS

The properties and failure mechanisms of AC pipes are closely related to their manufacture processes and chemical compositions. Free lime produced during the curing process is the critical factor in understanding the processes that contribute to the deterioration and failure of the pipes.

Pipe conditions can be assessed by means of several methods, including water quality, pipe sampling, non-destructive testing, and historical failure data analysis. Water quality methods are qualitative in nature. Pipe sampling methods such as phenolphthalein tests, elemental analysis and strength tests all measure direct, measurable condition parameters such as lime depletion depth and residual resistance strength and can accurately indicate pipe conditions. Non-destructive testing is at an early stage of development. Historical data analysis is a good approach for assessing pipe conditions if data are complete and integral.

Predicting remaining service life depends on two critical parameters: current condition and deterioration rate. Modeling deterioration rate is currently imprecise because of the considerable uncertainty involved in deriving the rate. Howver, overall, significant process has been made on techniques for predicting the remaining service life of AC pipe.

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