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FAILURE CONDITIONS OF ASBESTOS CEMENT WATER MAINS IN REGINA

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ABSTRACT: Approximately two thirds of the water mains in the City of Regina are asbestos cement (AC) pipes. These pipes are experiencing more and more failures in recent years and account for almost all of the water main breaks in the city. The AC water main failures, along with the failure of other types of water mains in general, are a result of various factors, some of which are site specific. To assess the condition and identify the factors that significantly influence the breakage of AC water mains, the historical failure data for AC water mains in the City of Regina have been collected, along with their corresponding working environments, including soil type, water quality, weather, etc. The AC water main break data were analyzed for correlation between pipe breakage and all known physical, environmental and operational factors. The predominant factors that influence the AC pipe breaks were identified. It was observed that pipe age, diameter, climate, soil and construction and repair methods all influence the condition of the AC water mains in Regina, with climate and soil conditions being the two critical factors. Water quality is not a major determinant of the AC water main condition for the city. The observations will serve as a basis for further research on the failure mechanisms of the AC pipes, which is essential for the performance prediction of these water mains and, therefore, the management of the city's AC water main assets.

1. INTRODUCTION

In the City of Regina, approximately 531 km, or two-thirds, of the water mains are asbestos cement (AC) pipes. These pipes are experiencing more and more failures in recent years and account for almost all of the water main breaks in the city. In many municipalities, AC pipes are replaced whenever their performance and condition warrant extensive repairs. This is not an option for the City of Regina because of its large inventory of AC water mains and funding constraints. To ensure that the city's administration can manage its AC water main assets to continue to provide an adequate supply of safe water in a cost-effective, reliable and sustainable manner, it is essential that a clear understanding be developed of AC pipe failure conditions and the mechanisms behind the failures.

The failure conditions and their corresponding mechanisms are dependent on a number of factors. These factors may be grouped into three general categories: (a) physical characteristics of the pipes themselves (e.g. flexural strength), (b) the environments in which the pipes are working (e.g. climate, soil type, groundwater properties, water table), and (c) operational characteristics (e.g. water quality, operation and maintenance, repair or replacement procedures) (NRC 2002; Rajani and Kleiner, 2001). The interplay of these factors determines the failure processes and modes. However, the role played by each factor may vary due to site-specific conditions. Therefore, identification of factors contributing to the occurrence of water main failures in a given site should be the first step towards understanding of the failure mechanisms.

Previous studies on the performance of AC water mains have stemmed from two concerns. One was a health concern related to the release of asbestos fibres into the drinking water due to chemical attack on the asbestos cement material and the erosion of the internal surface of the pipe by the water. It was found that in some environments, AC pipe materials are subject to damage due to various chemical processes that either leach out the cement material or penetrate the pipe wall to form products that weaken the cement matrix (Mordak and Wheeler 1988). Nebesar (1983) did a comprehensive review of these "corrosion" mechanisms in AC pipes. A number of chemical agents were identified including acids, sulphates, magnesium salts, alkaline hydroxides, ammonia and soft water. Some organic compounds were found to be "corrosive" as well. Pits and holes on pipe walls are indicators of corrosion. External corrosion of AC pipes follows the same principles as internal corrosion, i.e., pH, alkalinity, sulphates contained in the soils or groundwater will attack AC pipes (Jarvis 1998).

The other concern was related to the asset management of AC water mains, which requires a condition assessment of the pipes for determining the remaining service life and improving the service condition. AC water mains were observed to deteriorate with pipe age and a linear relationship was identified between the breakage rate and the pipe age (Kettler and Goulter 1985). It was also noted that the breakage rate of AC pipe was influenced by pipe diameter, with a lower breakage rate for larger diameter (Guan 1995, Mordak and Wheeler 1988), which was attributed to the thicker wall and higher bending moment resistance associated with larger diameter pipe (Mordak and Wheeler 1988). The greater wall thickness provided an inherently more robust pipe, which was not as likely to fail structurally as a result of chemical attack and external loading (Kettler and Goulter 1985).

AC water mains may also fail due to other operational, environmental and physical factors. For example, it was observed by Mordak and Wheeler (1988) that the distribution of failures through the year has been fairly random for areas where sandy/gravel soils commonly occur, whereas in areas with cohesive clay soils, most failures occur during the dry summer months. Cohesive clay soils are also associated with high incidence of circumferential fractures, which are commonly related to bending stresses. Construction/repair methods may also contribute to the failure of AC water mains (Mavin 1996; Guan 1995). Pipe breakage is more likely to occur when the environmental and operational stresses act upon pipes whose structural integrity has been compromised by corrosion, degradation, inadequate installation or manufacturing defects (Rajani and Kleiner 2001).

All the aforementioned studies show that AC water main failure, along with the failure of other types of water mains in general, is a result of various factors, some of which are site specific. To assess the condition and identify the factors that significantly influence the breakage of AC water mains in the City of Regina, the historical failure data of AC water mains in the city has been collected and analyzed, along with their corresponding working environments, including soil type, water quality, weather, etc. In this paper, the information was evaluated to determine the failure conditions of the AC water mains in the city. The predominant factors that contribute to the AC pipe failure were identified.

2. REGINA'S WATER DISTRIBUTION SYSTEM

2.1. History of the Water Distribution System

Regina, Saskatchewan, Canada, was founded in 1903 and had a population of around 200,000 in 2003. The earliest construction of the water distribution system was in 1904. Cast iron (CI) pipes were first used in the water distribution system and were predominant until the 1940s. The use of asbestos cement pipes was adopted in the middle 1940s and became predominant in the 1950s and 1960s. Since they were considered by the city to have better performance than CI pipes, AC pipes were used in all the new subdivisions, as well as to replace failed CI pipes.

In the early 1980s, health concerns with the asbestos fibres and the wide acceptance of polyvinyl chloride (PVC) pipe by the water works industry changed the landscape of the water distribution system in City of Regina. Since then, PVC pipes have been used in the construction of new developments and in the replacement of CI and AC pipes.

Besides CI, AC and PVC, steel pipes were also used. Steel pipes have a good service performance but are more costly. Most steel pipes in Regina are used for large diameter (> 500 mm) transmission mains. Other materials that were used to a much less extent are polybutylene and concrete.

Currently, Regina has approximately 753 kilometres of water mains within the city limits. These mains vary in size from 100 to 600 mm in diameter. With about 531 km in service, AC comprises about two-thirds of the total length of the pipe network. The length of AC pipe in service has not changed significantly since 1986, except for small reductions due to replacement during repairs. The pipe sizes for asbestos cement water mains in Regina include 100, 150, 200, 250, 300 and 400 mm. The 150 and 200 mm pipes comprise a large percentage of the system. There are only a few sections of 100 and 400 mm pipes.

2.2. Data Collection

The AC pipe repair information used in this study was acquired mainly from the Engineering and Works Department of the City of Regina. The original records show that the earliest installation of AC pipe was in 1945. With the development of the city and the construction of new residential, commercial and industrial areas, the water distribution system expanded. The dates of pipe construction, repair and replacement were recorded and are available for most streets. However, these records are not complete and some data are missing.

The data recorded on the water main repair report sheets include leak location, dates received and repaired, pipe material, size, leak type, repair material and length and connection information. Some particular situations were noted in a Remarks portion of the repair report. The installation year for each AC water main can be found on the Water Main Distribution System Map of the City of Regina. However, some AC pipes have been replaced with PVC pipes since the mid-1980s and the installation year data for the original AC water mains were not available.

3. CONDITIONS OF AC WATER MAINS

3.1. Installation of AC Water Mains

Figure 1 shows the length of AC pipes installed each year from 1945 to 1986. The annual installation lengths shown in this figure represent the AC water mains currently in service. Three peak periods can be identified in Figure 1. The first one is from 1953 to 1959 with around 20 km of AC water mains installed each year. The second one is from 1964 to 1966 with about the same length of AC pipes installed annually as the previous peak. The third peak period lasted from 1972 to 1980 with the highest annual installation length of 42.8 km of AC water mains in 1976 falling in this period.

The annual installation length for the period between 1983 and 1986 was reduced gradually to zero when use of PVC was fully adopted. It should be noted that the annual installation lengths may not be accurate, especially for the earlier period, because of water main repairs. Some AC water mains are likely to have been replaced during these programs and their records removed from the City's database.

3.2. History of AC Failure

The service condition of AC pipes is evaluated in terms of the number of breaks of water mains based on the available data collected by the City of Regina. The term "break" in this study is taken to correspond to an entry on a water main repair report sheet and constitutes a single repair event. The AC water main breaks during the period from 1994 to 2003 were analyzed and a total of 911 breaks were recorded for this period. Figure 2 shows the annual number of breaks. The plot indicates that the number of breaks has, in general, been increasing steadily. Also included in this figure is a fitted exponential curve. The good correspondence (the square of the correlation coefficient, R^2, =0.83) between the fitted curve and the historic data points indicates that the number of breaks is increasing at an accelerated (exponential) rate and the overall system condition is deteriorating.

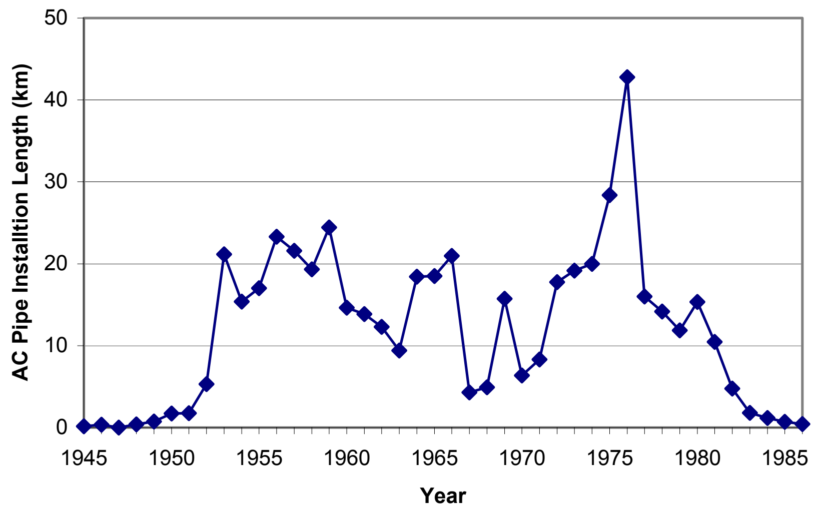

Figure 1. Annual installation length of AC water mains (1945 -1986)

The historic data plot shows that two peaks of breakage occurred in 2001 and 2003. The abnormal weather in these two years might be the major factor inducing more pipe breaks. In 2001, a record rainfall was noted in July followed by extremely low rainfall in August and September. City staff has reported that the higher number of breaks in 2003 might have been due to the high temperature and dry weather during the summer period of this year.

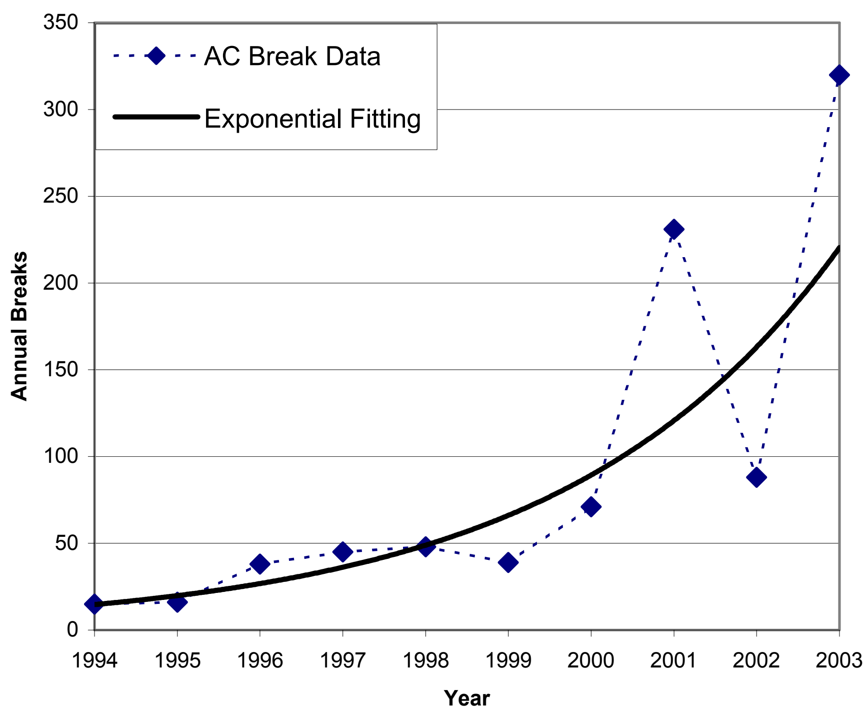

Figure 2. Break history of AC water mains (1994~2003)

3.3. Monthly Failure Conditions

The monthly breakage numbers are shown in Figure 3 for AC water mains in Regina. There are three curves, which represent the monthly break numbers for 2001, 2003 and the average number for the 10-year period from 1994 to 2003, respectively. The monthly break numbers for 2001 and 2003 are also included for comparison. This figure shows that high breakage rates occurred in August and September and sometimes in February and March. The highest breakage of water mains occurred in September.

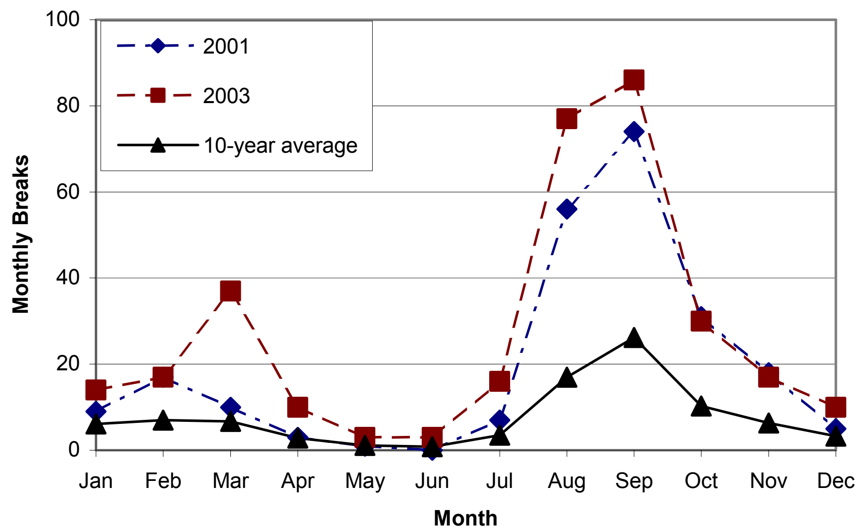

Figure 3. Monthly breaks of water mains in Regina fro 2001, 2004 and the 10-year average (1994 to 2003)

The higher breakage in the summer season for both normal and off-normal years may be attributed to different factors. The high temperature combined with relatively low precipitation will desiccate the soil, inducing shrinkage and, consequently, differential movement, uneven bending support and/or uneven loading conditions. More traffic in summer may also impose extra loading on the buried pipes. The second peak for the two off-normal years may be related to extended periods of cold temperatures in these particular winter seasons. If a decrease in the ambient temperature is sustained, the frost will penetrate deeper into the ground, causing increased frost loads on the buried pipes, even though they are buried at some distance below the maximum frost penetration depth (Bahmanyar and Edil 1983).

3.4. Spatial Failure Conditions

To assess the system failure condition in the entire city, the breakage distribution for the AC water mains in the city was investigated. Figure 4 presents the breaks of AC pipes during a one-year period in 2003. It can be seen from Figure 4 that the water main breakage was not evenly distributed within the city. The breakage of AC pipe was most serious in the southern areas. Other areas that have a high concentration of AC pipe breakage include the central, central west and northern parts of the city. These areas were the earliest ones constructed using AC pipes. The southeast and northwest areas were developed since the 1980s and PVC pipes were used.

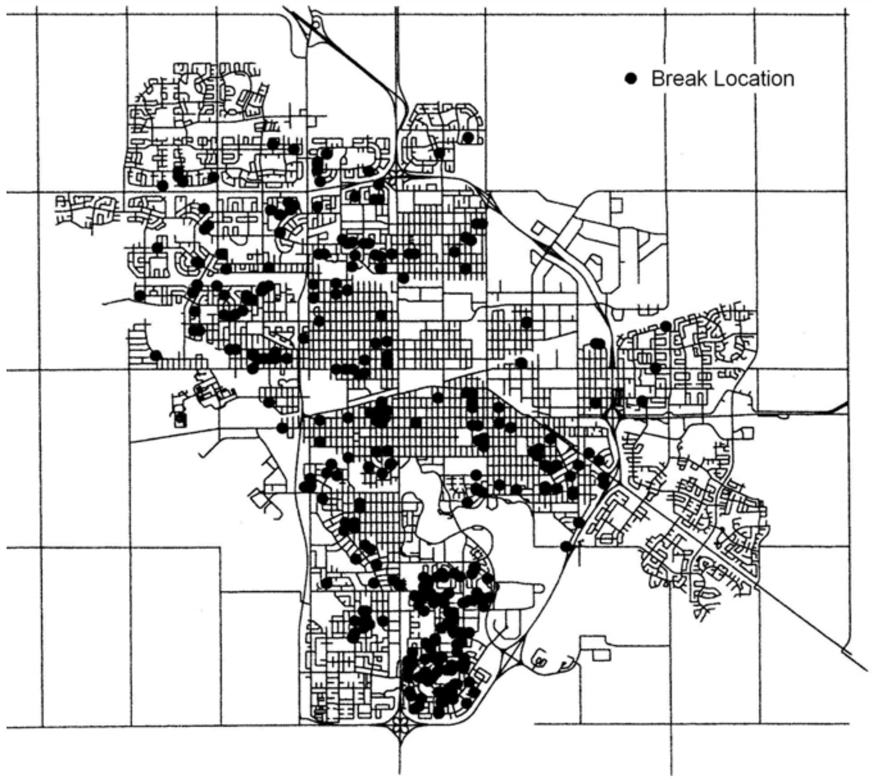

Figure 4. Water main breaks in 2003

There are a few factors that may account for the spatial pattern of AC water main breaks as shown in Figure 4. In addition to the earlier development period and greater age of the pipes, the pipe length per unit area in these areas may also be a factor, i.e., the areas with greater pipe length per unit area may have more breaks. The higher density of pipe breakage in the southern area may be affected by low elevation and soil conditions as well.

3.5. Failure Modes

All breaks are divided into five categories: longitudinal, circumferential, hole-in-main, pinhole and other. Although hole-in-main and pinhole are both primarily due to chemical attack, their failure modes are different in that a hole-in-main failure requires internal pressure or external loading whereas pinhole fails due to chemical attack only. A few breaks are characterized as “other”, which include everything from joint failure to subsequent leakage at a clamped repair location. Table 1 lists the different failure modes and their corresponding percentages. Among the 911 breaks from 1994 to 2003, circumferential breaks comprise the predominant failure mode (90.9%).

Table 1. Failure modes and their percentage

Failure Modes	Longitudinal	Circumferential	Hole-in-main	Pinhole	Other
Breaks	5	828	7	2	69
Percentage	0.5%	90.9%	0.7%	0.2%	7.6%

This table indicates that corrosion is not a big problem for the AC water mains, as the breaks due to corrosion (hole-in-main and pinhole) account for less than 1% of the total breaks for this period. Because the longitudinal break number is very small, internal water pressure, soil stresses and other circumferential loading (e.g., traffic) also do not have a major influence on the breakage of AC pipe. The high rate of circumferential failure suggests that axial bending (or beam action) is the predominant loading condition leading to failure.

3.6. Failure Pipe Size

The pipe breakage for different pipe sizes was also analyzed. Table 2 summarizes the break numbers of AC water mains for the four major pipe sizes (150, 200, 250 and 300 mm diameter) during the 10 year period, 1994 to 2003. Table 2 shows that most repair work was related to the 150 mm pipes and more than 94% of the breaks occurred in the 150 and 200 mm pipes. The City of Regina provided the 1993 percentages of the four pipe sizes: 62.4%, 21.1%, 10.7% and 5.8%, respectively (Guan 1995). Based on this information. When converted to the number of breaks per unit length (km) per year for AC water mains (Table 2) the break rate decreases with increased pipe size. This finding agrees with that of previous researchers, e.g., Mordak and Wheeler (1988), among others. For Regina, the rate for 150 mm pipes (0.22 breaks per km per yr) is nearly double the rate for 200 mm pipes (0.13 breaks per km per yr), which is nearly 4 times the rate for 250 and 300 mm pipe (about 0.04 breaks per km per yr).

Table 2 Number of breaks of various diameter pipes (1994-2003)

Diameter (mm)	150	200	250	300	Others*	Total
No. Breaks	719	149	20	14	9	911
Percentage	78.9%	16.4%	2.2%	1.5%	1.0%	100%
Breaks/km/year	0.215	0.132	0.035	0.044		

* Others include 100 mm, 400 mm and unknown pipe sizes (not recorded)

The reasons for the tendency for decreasing pipe breakage with increasing pipe diameter may be attributed to higher bending moment resistance associated with larger diameter pipes, as suggested by Mordak and Wheeler (1988). A greater diameter pipe with a larger moment of inertia will have lower bending stresses in the pipe if the external loading condition is the same and, therefore, will have less possibility of circumferential failure. A large wall thickness associated with a larger diameter pipe may not be important because chemical attack related breaks were only a small percentage of total breaks.

4. DISCUSSION

In the previous section, the failure conditions of AC water mains in the City of Regina were analyzed and the possible factors causing the failures were also discussed. Pipe age, size, climate and soil conditions were cited as possible factors which may influence the AC pipe conditions and cause them to break. These factors, along with other possible factors identified during the repair records review and field observations at repairs performed in the summer and fall of 2004, are discussed in this section.

4.1. Climate

Climate appears to be one of the most important factors contributing to the observed AC water main failure patterns. Two peaks in the historic data plot (Figure 2) are all related to off-normal climate conditions in 2001 and 2003, respectively. The higher number of breaks in 2003 corresponds to a hot summer with a long dry period. Abnormal weather was also observed in 2001, with a record rainfall in July followed by extremely low rainfall in August and September. The cyclic pattern of the monthly pipe breakage, as illustrated in Figure 3, may also be attributed to the seasonal cyclic pattern of climate changes in this region.

The summer season in Regina usually sees high temperatures and relatively low precipitation, especially in August and September. During these dry months, soil moisture is depleted due to evapotranspiration. A reduction in moisture content will result in shrinkage of the cohesive clay soils that are predominant within the Regina region and cause loading of the buried pipes. Additionally, the drying of the clay may reduce the attenuation of imposed traffic and other loads, leading to higher loads transmitted to the pipes. The relative effect of these factors in contributing to the high incidences of breaks in summer, especially those in 2001 and 2003, requires further study.

Figure 3 also shows that a second peak in pipe break number occurs during the coldest period of the year for both of the abnormal years. This phenomenon has been observed by many researchers, including Rajani and Zhan (1996) and Selvadurai and Shinde (1993). It has been attributed to increased earth loads on the buried pipes due to freezing and expansion of the water in the ground. The process involves not only the water near the freezing front (0°C isotherm), but also the moisture around the front through migration towards the freezing front (Shah and Razaqpur 1993). A loss in moisture, as discussed previously, will further worsen the environment of water mains by causing soil movement around the pipes. In addition, a decrease in temperatures external to the pipe during the winter season will cause an increase in pipe tensile stress (Zhan and Rajani 1997). The very cold temperatures in the winter season of 2001 and 2003 may have contributed to the second peak of breaks that occurred in these two years.

4.2. Soil

The clay soil in the Regina region is a Montmorillonite type clay and consequently has high rates of volumetric shrinkage and expansion due to changes in moisture content. The change in soil volume will result in soil movement, which, in turn, induces additional stress on buried pipes. The soil movement may cause these stresses through different mechanisms, such as non-uniform bedding support and differential settlement. Since non-uniform soil bedding support or differential soil settlement is typically related to axial bending or beam action, it is expected that bending-related failures will be significant, especially during the period when greater soil moisture change occurs. The high incidence of circumferential failures (Table 1) and the large proportion of failures on small diameter mains (Table 2) are consistent with such external loading imposing bending stresses on the pipes.

Besides climate (temperature and precipitation), other factors may also cause change in moisture content, including water uptake by vegetation (e.g., roots of large trees), pipe leakage and other activities, such as pipe repairs.

4.3. Corrosion

In general, the water transported inside the pipes and the external soil and ground water conditions can influence the condition of asbestos cement pipes. The total breaks due to corrosion (Hole-in-main and Pinhole, as presented in Table 1), represent only 1 percent of the total number of failures, indicating that corrosion is not an important factor in AC water main failure in Regina. The non-corrosive environment was confirmed by exhumed AC water mains showing smooth internal surfaces even after 50 years in service.

4.4. Pipe age

The annual break curve of AC water mains (Figure 2) indicates that the system condition is deteriorating with time, especially in recent years. Since all the impacts induced by the physical, environmental and operational factors will accumulate with time, it is expected that more breaks will occur with increased pipe age. Therefore, the age of water mains is expected to be a overall factor affecting pipe breakage. However, the actual mechanisms behind the age effect have not been separately evaluated and these factors require further study.

4.5. Other factors

Other factors may include construction specifications and practices, operating pressures, manufacturing processes, traffic, etc. For example, the variable stresses due to traffic loading may induce pipe breakage by fatigue action. The increased breaks in August and September may also be due to the increased traffic volume in the summer season.

5. SUMMARY AND CONCLUSION

The historical failure data for asbestos cement water mains in the City of Regina were analyzed for the period from 1994 to 2003 to assess the condition and identify the factors that significantly influence the breakage of these water mains. The failure data suggest that the condition of the AC water mains in the City of Regina is deteriorating, with the number of failures increasing annually at an exponential rate during the 10-year period. Years 2001 and 2003 have recorded the two highest water main break numbers in history, due to particularly abnormal climate conditions in these two years. Most of the breaks occurred during the dry summer months and the cold winter months. Circumferential breakage was the predominant failure mode.

Uneven spatial and temporal patterns of AC water main breaks in the city were also observed. Pipe breakage was concentrated in a few subdivisions such as the central, central-west, northwest and southern areas. Water quality was not found to be an important factor in terms of pipe corrosion.

The primary causes behind the AC water main break patterns are attributed to the properties of the Regina clay and the local climate. Regina clay has a very high swelling and shrinkage potential upon moisture change. The high expansive characteristics of Regina clay coupled with a reduction of soil moisture content in summer contributes to the high incidence of pipe breaks in summer seasons and the break peaks in the driest years. Frost load and temperature change may have contributed to the relatively small peaks in breakage noted during the winter months.

Pipe diameter, age and other construction specifications and practices are also important factors when the pipe failure patterns in Regina were analyzed. These factors may influence the pipe failure patterns themselves and the effect may become more severe by combining with particular soil and climate factors. Further study of the contributing factors identified in this study will lead to a better understanding of the failure mechanisms, which is essential for the performance prediction of these water mains and, therefore, the management of the city's AC water main assets.

6. ACKNOWLEDGMENTS

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