EXECUTIVE SUMMARY

BACKGROUND AND INTRODUCTION

As water mains become old and reach the end of their useful lives, their performance diminishes gradually, resulting in high maintenance costs, deterioration of water quality, loss of hydraulic capacity, and a significant increase in customer complaints. Cleaning and lining of a poorly performing water main will decrease customer complaints and will improve water quality, flow, and pressure significantly. This will improve the long-term performance of the pipe and improve the reliability of the system. Rehabilitation of water mains using cleaning and lining results in significant cost savings compared to replacement.

In North America, most of the water main rehabilitation is conducted using cement-mortar lining. Alternatives to cement-mortar lining of water mains are epoxy lining and polyurethane lining.

In the United Kingdom (U.K.), epoxy has been used as the preferred lining material in rehabilitation of water pipelines. In the last few years, however, polyurethane has become the most widely used lining material in the U.K.

One of the important purposes of pipe lining is to prevent leaching of metals from the wall of water mains and thus, to improve water quality. However, there is concern about potential leaching of metals and organic chemicals from these lining materials. Water quality problems as a result of leaching chemicals from these linings are of great concern in the United States. A few years ago the National Sanitation Foundation (NSF) provided the approval certification (NSF-61) for use of epoxy and polyurethane as viable alternatives to cement-mortar lining for drinking water mains. Water quality impact cost may be significant but, in general, is not considered in selection of lining materials. When comparing the cost of alternative lining materials available for water main rehabilitation, it is necessary to consider the water quality impact cost while estimating the total cost of the lining.

Water quality impacts of lining materials may be an important decision criterion in selecting a lining material or rehabilitation technique. In this study a methodology for a decision support system for selection of an appropriate lining by water utilities that considers potential water quality impacts has been developed.

OBJECTIVES OF THE RESEARCH

The objectives of this study were the following:

- Gather, compile, and synthesize detailed information on water quality impacts associated with cement mortar, epoxy, and polyurethane water main lining materials and conduct bench-scale testing of water quality impacts of newly laid cement mortar, epoxy, and polyurethane lining materials under various exposure times and water characteristics.
- Develop a methodology to help water utilities to consider water quality impacts in order to select the most suitable lining rehabilitation method for long-term performance.

- Identify research needs and knowledge gaps on water quality impacts from lining materials.

RESEARCH APPROACH

The research approach to accomplish the project objectives and goals consisted of the following tasks:

- A comprehensive review of literature and available information was conducted to study literature on water quality impacts from cement-mortar, epoxy, and polyurethane lining rehabilitation methods.
- A group of selected water utilities with water main lining experience were contacted to conduct a questionnaire survey of historical lining rehabilitation projects and their impacts on water quality. Data were compiled and evaluated to identify principal parameters impacting water quality.
- A bench-scale leaching study was formulated and conducted with cement-mortar, epoxy, and polyurethane lining materials, and water quality impacts were evaluated. In addition, leaching tests with one mature sample of epoxy lining was conducted to evaluate impacts of age of epoxy lining on water quality.
- Information gathered was evaluated and a methodology was developed to identify water quality impacts due to various lining materials, and to estimate the cost of such impacts for selection of cost-effective lining rehabilitation technologies. The methodology has been applied to one test case utility to demonstrate its suitability and applicability.
- Knowledge gaps were identified, and findings and recommendations were made.

SURVEY OF CURRENT PRACTICES

A questionnaire survey of water utilities of North America and the U.K. was conducted. North American water utilities installed epoxy lining in about 100,000 feet (ft) of water mains, whereas, the U.K. utilities constructed about 50,000,000 ft of water mains. Utilities surveyed used cement-mortar, epoxy, and polyurethane linings. The need to improve water quality was found to be the primary reason for lining water mains. Significant improvement in water quality and hydraulic performance was observed by water utilities after installation of liners. All surveyed utilities reported to have a good written quality assurance/quality control (QA/QC) procedure and conduct a closed-circuit television (CCTV) inspection of water mains before and after the lining.

DESIGN OF BENCH-SCALE STUDY

Bench-scale testing was undertaken that simulated the water volume to surface area ratio of a 4-inch (in.) diameter pipe. Coupons of the lining materials were used in these tests. The bench-scale testing used low alkalinity/low hardness water with either no disinfectant, free chlorine, or chloramines. Four water types were tested for cement-mortar lining and three water types were tested for epoxy and polyurethane linings. Complete water changes occurred on days 1, 2, 4, 9, 11, 14, 15, and 19; the tests continued up to 30 days with occasional water changes from day 19 to day 30. The contact times between the water and lining materials represented worst-case conditions similar to those in low flow and dead-end water mains.

TESTING OF CEMENT-MORTAR LINING

The following are the water types used in testing cement-mortar lining:

- pH = 8.0, low alkalinity/hardness, no disinfectant
- pH = 6.5, low alkalinity/hardness, 2.0 mg/L chlorine
- pH = 8.0, low alkalinity/hardness, 2.0 mg/L chlorine
- pH = 8.0, low alkalinity/hardness, 4.0 mg/L monochloramine

The main water quality impact of cement-mortar linings is to increase pH, alkalinity, calcium, aluminum, and total dissolved solids (TDS). The duration of the increases in alkalinity, calcium, aluminum, and TDS lasts from 2 to 4 weeks. The impact on pH is more persistent, lasting more than 30 days.

The cement-mortar material created a significant increase in the alkalinity of all four test waters. The impact on alkalinity in general terms was the same for all four test waters increasing it to 600 milligrams per liter (mg/L) as $CaCO_3$ and then stabilizing at 100 mg/L after day 19 of the test. The background alkalinity of the test waters was 35 mg/L.

Cement mortar increased the pH with nearly identical values for all four test waters. The starting pH of test waters did not impact the resulting pH after contact with the cement mortar. The pH after the first day in contact with the cement mortar was 12.4. After 30 days in contact with the cement mortar and 9 changes of water, the pH was 11.5.

Cement-mortar increased the calcium concentrations in the test waters. Increased concentrations of calcium were measured over a 14-day period, after which calcium stabilized and remained at 7 to 9 mg/L as calcium, slightly below the background concentration of 11.5 mg/L as calcium.

The aluminum concentrations increased in all four test waters after being in contact with the cement-mortar coupons, showing the same trend in the increase. The aluminum concentrations increased from day 1 through day 9, then decreased significantly at day 11 of the test, probably due to a lower contact time of 2 days. The concentrations of aluminum exceeded the drinking water secondary maximum contaminant level (SMCL) of 200 micrograms per liter (µg/L) for the first 9 days of the test.

The chromium concentrations increased to 0.07 mg/L in 24 hours, but decreased significantly on day 9. Cement-mortar lining increased consumption of chlorine. Chloramines were more stable than chlorine in the presence of cement mortar.

The total solids (TS) concentrations increased up to 1,500 mg/L on the first day and declined substantially after day 9.

Cement-mortar lining was also tested with Corrosion Prevention Additive (CPA) waters to find its impact on water quality parameters of pH, alkalinity, and metals from newly installed cement-mortar lining. The three different CPA chemical regimes used are:

- Orthophosphate (OP) at 1.0 mg/L as P
- Polyphosphate (PP) at 1.0 mg/L as P
- Orthophosphate and zinc (OPZn) at 1.0 mg/L as P and 0.3 mg/L as Zn

Results show that the pH of all three tests increased to 12 and then dropped in the range of 10.65 to 11.3. The alkalinity of all samples increased to 800 mg/L as $CaCO_3$ and dropped to about 100 mg/L as $CaCO_3$. Similarly the hardness of all samples increased to 600 mg/L as $CaCO_3$ and finally dropped to less than 100 mg/L as $CaCO_3$.

TESTING OF POLYURETHANE LINING

Three standard water compositions were tested before and after contact with polyurethane-coated coupons. The three water types were:

- pH = 8.0, low alkalinity/hardness, no disinfectant
- pH = 8.0, low alkalinity/hardness, 2.0 mg/L chlorine
- pH = 8.0, low alkalinity/hardness, 4.0 to 6.0 mg/L monochloramine

In the presence of polyurethane, the pH was reduced from pH 8 to about pH 6. The pH drop was observed within 24 hours and persisted for 30 days.

Polyurethane consumed chlorine and chloramine disinfectant although chlorine was consumed at a greater rate than chloramine. The consumption rate decreased over time, but still persisted at the end of 30 days of testing.

Organic carbon was leached from polyurethane, with a greater amount leached in the presence of chlorine than in its absence. Leached total organic carbon (TOC) reacted with free chlorine to form up to 30 µg/L of five regulated haloacetic acids (HAA5), but no trihalomethanes (THMs) were detected. The low pH of 6 would favor HAA5 formation over THM formation. None of the THM or HAA5 concentrations exceeded the drinking water standard of 80 µg/L and 60 µg/L, respectively.

Weak to moderate odor intensities were released from the polyurethane and it persisted for the 30 days of this study.

TESTING OF EPOXY LINING

Three standard water compositions that were tested with epoxy-coated coupons were the same as those tested with polyurethane lining.

The greatest impact from epoxy was on TOC and disinfectant residual concentrations. Epoxy exposed to each of the three water types produced significant concentrations of TOC (3.5 to 6.3 mg/L) during the first 24 hours of exposure to water. By the second 24-hour exposure period the TOC decreased substantially. By the end of the 30 days, each of the water types exposed to epoxy had TOC present in concentrations between 0.5 and 1.7 mg/L, with chlorinated water having the highest TOC concentration.

Epoxy reduced the concentrations of both chlorine and chloramine disinfectants. Free chlorine was consumed at a greater rate than chloramine. Mature pipe samples lined with epoxy also reduced the disinfectant residual concentrations.

Water exposed to epoxy showed some increase in the THM and HAA5 concentrations, but none of these increases exceeded the drinking water standards. The increases in THM and HAA5 concentrations were greatest in the chlorinated water.

METHODOLOGY

A simplified procedure that provides guidance to water utilities in the selection of lining materials for pipe-lining projects was developed. The methodology incorporates water quality impacts, useful life of alternative lining materials, and comparative costs of water quality impacts. The methodology includes a procedure for estimating the water quality impacts from lining materials using the following three procedural steps:

- Convert concentration increases to daily rates
- Calculate mass leaching rates in milligrams per square centimeter per day ($mg/cm^2/day$)
- Apply mass rates to distribution-system-scale conditions

In this methodology, bench-scale study data of water quality impacts were first converted into daily rates. These data were then used to develop mass leaching rates in $mg/cm^2/day$ for all important parameters and lining materials. This procedure has been applied to each major water-quality-impacted parameter identified in the bench-scale tests for each of the three lining materials. Calculated mass rates were then applied to estimate water quality in distribution system water mains. For each water main, pipe size and average flow data are required to analyze turnover time or contact time. This information provides the user the duration of a particular parameter concentration above the accepted limit prescribed by the utility. Analyzing all the major water quality parameters for cement-mortar, epoxy, and polyurethane linings, a worst-case scenario for each lining material requiring maximum flushing was identified. The procedure includes the ability to calculate the volume of additional flushing required to keep the water quality to a desired level. Once a water quality impact mitigation plan is developed, the costs of any additional required flushing are estimated.

The whole procedure was developed in two easy-to-use spreadsheets labeled as "Impact Module" and "Cost Module" to help water utilities to analyze the suitability of alternative lining materials and the relative water quality impact cost of each option in order for them to select a cost-effective lining material.

TEST CASE STUDY

The Impact Module software developed in this study for evaluation of cost effectiveness and suitability of a lining material was tested with South Central Connecticut Regional Water Authority's (SCCRWA) data for a lining project to determine the applicability of the software in determining a suitable lining material.

An SCCRWA lining project was selected and required data on pipe size, length, and average flow. Background water quality parameters were collected and applied to the software to determine the water quality impacts of each liner and the relative costs of mitigation in order to identify the most suitable lining material for the project.

The software developed was able to calculate water quality impacts, and the relative costs for each lining material and helped to select the most suitable liner. The test case results indicate that the water quality impacts from the three lining materials were minimal.

FINDINGS

The following are the important findings and recommendations of this study:

- A survey of North American and European water utilities conducted for this study indicates that North American water utilities have experience primarily in using cement-mortar lining, whereas in Europe most of the water utilities use epoxy and polyurethane linings. The most frequently reported water quality impact from cement- mortar lining was an increase in the pH of the water.
- Cement-mortar lining:
    - Impacts to water quality from cement mortar were most severe up to 9 days. After day 9, a significant decrease in most water quality parameter release rates was observed.
    - The pH of water increased drastically to a value of 12.5 with 24 hours of contact with cement mortar and maintained values of pH 10.5 to 11.5 throughout the 30-day test period. Likewise, the alkalinity increased from 35 to 600 mg/L (as $CaCO_3$) within the first 24 hours of contact time with cement mortar. After 9 days of contact, the alkalinity declined to about 100 mg/L as $CaCO_3$.
    - The total solids content of the water increased to up to a maximum of 1,760 mg/L in the presence of cement-mortar coupons.
    - Cement mortar significantly increased the calcium, aluminum, and chromium concentrations in the water. The aluminum concentrations exceeded the U.S. Environmental Protection Agency (EPA) SMCL, while the chromium levels remained below the EPA maximum contaminant level (MCL). After day 9, release of aluminum and chromium to the water decreased.
    - Cement mortar created a substantial chlorine demand, but the demand for chloramine was much less and ceased after a few days of contact.
- Cement-mortar lining with corrosion prevention additives (CPA) in water: The findings of differences in the effects produced by any of three CPAs types when compared to a control are:
    - Polyphosphate (PP) reduced pH increases more substantially than orthophosphate (OP) or zinc orthophosphate (OPZn) after day 9.
    - There are no significant differences in increase of alkalinity, hardness, and calcium concentrations among various CPAs.
    - The magnesium (Mg) concentration is highest and aluminum (Al) is lowest for the PP additive.
- Polyurethane:
    - In the presence of polyurethane, the pH was reduced from pH 8 to about pH 6. The pH drop was observed within 24 hours and persisted for 30 days.
    - Free chlorine was consumed in the presence of polyurethane. The rate of chlorine decay was greater during days 1 through 4 than in later exposure times.
    - TOC was leached from polyurethane, with a greater amount leached in the presence of chlorine than in its absence. Leached TOC reacted with free chlorine to form up to 30 µg/L HAA5, but no THMs were detected.

  - Weak to moderate odor intensities were released from the polyurethane and it persisted for the 30 days of this study.
- New epoxy:
  - Epoxy exposed to each of the three water types produced significant concentrations of TOC (3.5 to 6.3 mg/L) during the first 24 hours of exposure to water and then the TOC decreased substantially.
  - The epoxy reacted readily with both chlorine and chloramines during the first 24 hours of exposure. The disinfectant consumption rate decreased over the 30 days. Disinfectant byproducts (DBPs) were present in most samples, with the highest concentrations detected in chlorinated water.
  - Bis-phenol A (BPA) was detected in concentrations of 22 to 33 μg/L during the first 24 hours in all three waters exposed to epoxy. Concentrations decreased substantially by test day 2.
  - Weak to moderate odor intensities were released from epoxy exposed, which persisted all 30 days.
- Mature epoxy:
  - Free chlorine exposed to the mature pipe was almost completely consumed by each test day. In contrast to the new epoxy, the pipe did not show a decrease in disinfectant demand over the 30 days.
  - TOC leached from the mature pipe sample ranged in concentration from 3.5 to 1.6 mg/L.
- Test case study: Hydraulic residence time (HRT) is a key parameter in controlling water quality impacts from lining materials.

RECOMMENDATIONS

The following general recommendations are made as a result of this study:

- The methodology developed in this study should be used to analyze water quality impacts of the alternative lining materials cement-mortar, epoxy, and polyurethane, and to rationally select a lining material. Cement-mortar lining, in general, should be avoided in low water circulating areas such as dead ends. In such areas, water should be flushed regularly. In other areas, water should be flushed initially. The frequency and duration of flushing can be determined by using the methodology developed in this study.
- Epoxy lining and polyurethane lining for water mains have been found to be good alternatives to cement-mortar lining and all water utilities should consider these technologies as an alternative to cement-mortar lining.