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Chlorine decay in drinking-water transmission and distribution systems: Pipe service age effect

*A.O. Al-Jasser**

Civil Engineering Department, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

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ABSTRACT

Water quality can deteriorate in the transmission and distribution system beyond the treatment plant. Minimizing the potential for biological regrowth can be attained by chlorinating the finished water. While flowing through pipes, the chlorine concentration decreases for different reasons. Reaction with the pipe material itself and the reaction with both the biofilm and tubercles formed on the pipe wall are known as pipe wall demand, which may vary with pipe parameters. The aim of this paper was to assess the impact of the service age of pipes on the effective chlorine wall decay constant. Three hundred and two pipe sections of different sizes and eight different pipe materials were collected and tested for their chlorine first-order wall decay constants. The results showed that pipe service age was an important factor that must not be ignored in some pipes such as cast iron, steel, cement-lined ductile iron (CLDI), and cement-lined cast iron (CLCI) pipes especially when the bulk decay is not significant relative to the wall decay. For the range of the 55 years of pipe service age used in this study, effective wall decay constants ranged from a decrease by −92% to an increase by +431% from the corresponding values in the recently installed pipes. The effect of service age on the effective wall decay constants was most evident in cast iron pipes, whereas steel pipes were less affected. Effective chlorine wall decay for CLCI and CLDI pipes was less affected by service age as compared to steel and cast iron pipes. Chlorine wall decay constants for PVC, uPVC, and polyethylene pipes were affected negatively by pipe service age and such effect was relatively small.

1. Introduction

Disinfecting drinking water is considered important for the maintenance of water quality in transmission and distribution systems. Treated water is disinfected before it enters the transmission system (Clark and Coyle, 1990). Because bacterial contamination of water can be expected in the transmission and distribution system, a detectable disinfectant residual should remain in the water so that the potential for waterborne disease and biofilm growth will be minimized. Previously, the Water Research Centre (1976) had suggested some considerations for controlling bacterial numbers in treatment and distribution systems; these include system cleaning, limiting the retention time of the water in the network and the use of alternative disinfectants which may persist longer in the water.

Due to its low cost, stability, and effectiveness, chlorine is widely used for disinfecting water. Generally, a free chlorine residual in excess of 0.2 mg/l must be maintained in the distribution system, thus reducing the likelihood of further contamination. However, chlorine concentration decreases with time due to consumption. Clark et al. (1993) stated that the chlorine residual can virtually disappear at various times during the day. Maul et al. (1985a) concluded that the

*Tel.: +966 555 60 58 59.
E-mail address: ajasser@ksu.edu.sa.
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occurrences of the highest bacterial concentrations are attributed to lower levels of chlorine residuals and prolonged retention time of the water in the network. This temporal and spatial consumption of chlorine is caused by chemical reactions of the chlorine with water constituents and with both the biofilm and tubercles formed on the pipe wall, as well as reaction with the pipe wall material itself (Wable et al., 1991; Zhang et al., 1992; Kiéné et al., 1998). Deposits, corrosion by-products (Zhang et al., 1992; Kiéné et al., 1998; DiGiano and Zhang, 2005), microorganisms (Wable et al., 1991), organic impurities, ammonia compounds, and unremoved metallic compounds, such as iron (ferrous ions) and manganese, are among the constituents of water that react with chlorine and lead to its disappearance. Reaction with the pipe material itself and the reaction with both the biofilm and tubercles formed on the pipe wall are known as pipe wall demand. DiGiano and Zhang (2005) pointed out that reaction of chlorine on the scales coating the inner pipe surfaces is the main reason for the loss of such disinfectant within distribution networks. These reactions cause a decrease in the chlorine content in the water. Maul et al. (1985a) observed that there was a rapid decrease in both free and total chlorine residual in the water in the distribution system, as residence time increases while travelling from the treatment plant. Haas et al. (2002) observed that chlorine residuals loss averaged about 40% after 24 h of disinfecting of new pipes at high chlorine concentrations, such as during mains disinfection. The studies of Maul et al. (1985a, b) showed that free and total chlorine residuals decrease rapidly as distance from the treatment plant increases and free chlorine residuals disappear in the peripheral sections of the distribution system. Moreover, chlorine decay rates increase with an increase in water temperature. The results of the study on the Little Rock distribution system show that free chlorine residuals at 23 °C were less than the corresponding concentrations at 0–4 °C (Kirsch et al., 1994).

Chlorine consumption has been classified as occurring in two phases (Zhang et al., 1992; Kiéné et al., 1998). The first phase occurs during the first 1–2 or 4 h (Jadas-Hecart et al., 1992) and corresponds to reactions of the chlorine with easily oxidizable compounds. This is normally completed in the reservoir of the treatment plant. The second phase, or long-term chlorine consumption, is slower than the first phase and occurs in the distribution system. The second phase is normally described in terms of an apparent first-order equation (Wable et al, 1991; Biswas et al, 1993; Rossman et al., 1994; Kiéné et al., 1998) as follows:

$$\frac{dC}{dt} = -kC, \tag{1}$$

where dC/dt is the of chlorine decay, mg/l per day, k, chlorine first-order kinetic constant or first-order decay coefficient, day^{-1}; C, chlorine concentration at time t, mg/l.

By integrating Eq. (1) and letting C equal C_0 when time t equals 0, the first-order kinetic equation used to describe chlorine loss is as follows:

$$C = C_0 e^{-kt} \quad \text{or} \quad \operatorname{Ln} C = \operatorname{Ln} C_0 - kt, \tag{2}$$

where C_0, initial chlorine concentration, mg/l; t, time, days.

With respect to wall decay, DiGiano and Zhang (2005) concluded that a zero-order overall kinetic model was well suited for describing the overall chlorine decay in a heavily tuberculated cast iron pipe, whereas, first-order overall kinetic model was found suitable for new cement-lined ductile iron (CLDI) pipe. AWWARF (1996) defines the overall chlorine decay constant during the second phase to be the sum of the first-order bulk decay constant, k_b, and the effective chlorine wall decay constant, k_w, which has been used by other researchers (e.g., Rossman et al., 2001; Hallam et al., 2002). Previous research has assumed first-order chlorine wall decay (Wable et al., 1991; Biswas et al., 1993; Rossman et al., 1994; Clark et al., 1995; Kiéné et al., 1998) and been found to be characterized by first-order kinetics (Vasconcelos et al., 1996). Vasconcelos et al. (1996) found that a zero-order wall decay kinetic reaction was effective for characterizing the wall decay, but also indicated that the first-order model might be better. This manuscript assumes the overall, bulk, and wall chlorine decay constants will be of first-order kinetics.

Relatively few studies have been conducted concerning the determination of the chlorine disappearance rate in distribution systems. These studies have been conducted either in the field or in the laboratory. Field studies are normally carried out by isolating the pipe under study from the network and by monitoring the chlorine concentration upstream and downstream. Chlorine may be injected upstream. By knowing the time of passage (retention time), the first-order decay constant in the pipe, due to both the water and pipe consumption, can be determined using Eq. (2). This constant is described as the apparent or total decay constant. Though on-site studies are considered directly applicable to the distribution system as they are performed under field conditions, large potential measurement errors are expected (Hallam et al., 2002). Laboratory studies are conducted by performing the test in pipe sections and monitoring the chlorine concentration with time. Menaia et al. (2003) studied the influence of flow velocity on chlorine consumption rate using a closed loop 120-m long, with 25-mm (1-in) diameter PVC pipe. Haas et al. (2002) described the decay of chlorine residuals in new ductile iron and PVC pipes following disinfection at levels as practiced during mains disinfection (up to 100 mg/l of chlorine). Hallam et al. (2002) performed their study on different pipe materials in situ as well as in the laboratory and claimed that the laboratory and the in situ results were similar. Rossman et al. (2001) performed tests in unlined ductile iron pipe loop to simulate field conditions. The pipe used was in service for several years and subjected to significant corrosion and biofilm buildup. A recent study was carried out by DiGiano and Zhang (2005) that investigated the effect of the velocity and water quality (corrosion rate, dissolved oxygen, and pH) on the decay rate of chlorine at the pipe wall of old cast-iron and new CLDI.

Kiéné et al. (1998) presented the relative importance of some parameters, namely, total organic carbon, and water temperature, pipe material, biofilm, and corrosion process, which are responsible for chlorine disappearance in network systems. Zhang et al. (1992) performed a field study on three pipe segments, one asbestos cement (500 mm in diameter) and two steel (700/800 and 500 mm in diameter), from the

Macao distribution network. They concluded that chlorine consumption by these pipes is negligible. Wable et al. (1991) performed a field study on three pipes of the Paris distribution network. They pointed out that in pipes transporting water with high organic content, the transfer of the organic matter between water and pipe surface is important and creates free chlorine consumption at the pipe surface.

As the chlorine decay in pipes is expected to change with the service age of the pipe in the system, the work presented in this paper was directed towards the determination of the influence of the service age of pipes of different materials and sizes on the effective first-order chlorine decay constant. In addition, the determination of the influence of the pipe service age on the effective first-order chlorine decay constant for chlorine consumption caused by the pipe material alone was also endeavoured.

2. Materials and methods

In order to accomplish the aim of this study, more than 350 pipe sections were collected. Out of these, 302 pipe sections were selected, prepared as described below, and used for performing the experimental work. These pipe sections were either new (i.e. not used before), recently installed, or old pipes of different ages from an actual system. The last two types of pipes were recently in service and were collected from the local distribution system as part of repair or rehabilitation works on existing pipes. The distribution system receives the same water which is composed mainly of water from desalination plants located at the Western coast of the Kingdom of Saudi Arabia and relatively small fraction (less than 3%) from well waters. The two sources are mixed together before entering the network. New unused pipes will be referred to in the remaining part of this paper as unused pipes. To avoid drying of the internal surface of the pipes, collected pipes were left in a tap water bath until the time of testing.

Eight different pipe materials were used in the study: cast iron, steel, asbestos cement, cement-lined cast iron (CLCI), CLDI , polyvinyl chloride (PVC), unplasticized polyvinyl chloride (uPVC), and polyethylene. Pipes ages ranged from new to 55 years old. Pipes diameters ranged from 12.5 (0.5 in) to 300 mm (12 in). All pipes were cut to a length of 1 m.

Each pipe section was cleaned with tap water and mounted on a chlorine consumption-free glass sheet and sealed (Fig. 1). Prepared sections were filled with chlorinated source water, made of sodium hypochlorite added to unchlorinated source water, the resulted chlorine concentration equals to that used during the decay test, left full for a few minutes and finally rinsed with water with a circa 2-mg/l chlorine concentration. Such action was done to avoid the initial chlorine demand by the pipe wall, which is expected to occur due to the presence of oxidizable compounds on the surface of the pipe wall (Kiéné et al., 1998).

Pipe sections were randomly divided into 61 groups. Pipe sections of each group were tested in parallel. At the time of testing, the top surface was covered with a glass sheet similar to that used for the bottom surface and sealed. A sample-suctioning tube and stirrer shaft were inserted through the top glass cover sheet. Before use, the glass sheets used for the top and bottom covers had been cleaned, soaked in a chlorinated source water, described above, with a chlorine concentration of about 5 mg/l, and washed with water with a chlorine concentration equal to that used during the decay test.

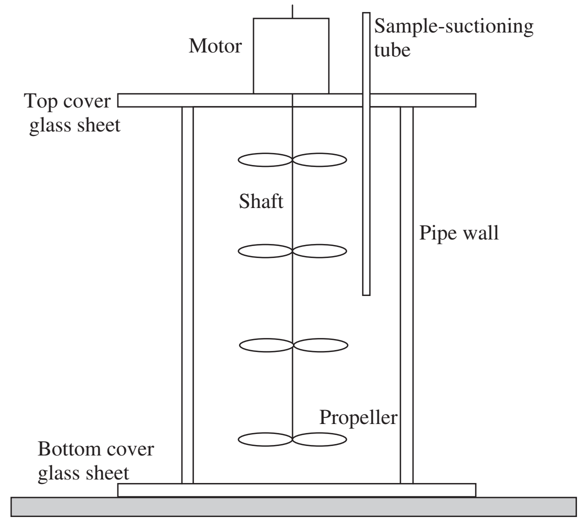

Fig. 1 – Schematic of the experimental set-up.

Chlorinated source water with a chlorine concentration of more than 2 mg/l, was prepared and left for about 2 h for the first phase chlorine demand by the water as described in the introduction. When chlorine concentration reached 2-mg/l, the water was poured into the pipe section. The 2 mg/l concentration was enough to avoid any incomplete demand by the pipes tested. However, such a concentration was not so high as to cause an inconsistency between actual field conditions and lab conditions. A stirring device made of four propellers fitted on a vertical shaft at equal spaces, and small motor to rotate the shaft. Different sizes of propellers were used. In any pipe section, propellers diameter is about 50% of the pipe diameter. This is to insure almost completely mixed regime in the pipe section and avoid unequal effect of hydraulics on the results.

While stirring, the change of free residual chlorine concentration with time was monitored by testing periodically withdrawn samples. The sampling program was stopped when the chlorine residual concentration became low, about 10% of the initial concentration. However, if this concentration was not reached within 3 days, sampling was terminated. The maximum chlorine concentration at termination was 0.63 mg/l. For some of the pipe sections, the chlorine concentration end point was reached after 30 min. The frequency of grab sampling was higher at the beginning and decreased gradually over time, ranging from 1 to 10 min during the first hour and from 1 to 4 h beyond the first hour during the first day, and from 4 to 10 h thereafter. Sampling frequency was adjusted so that the difference between any two consecutive concentrations was about 0.1 mg/l. Samples were tested immediately after collection. Free residual chlorine concentration was measured using a Hach spectrophotometer model DR-2010 with the DPD method.

Since a first-order overall chlorine decay constant is assumed, the first-order kinetic constant for chlorine decay is equal to the negative value of the slope of the best fit of the plots drawn for Ln(C) versus time. The chlorine decay constant determined from the data collected from tests in the pipe sections corresponds to both the consumption by the pipe wall and by water constituents and is called the overall decay constant.

The first-order kinetic constant for chlorine consumption by the constituents of the water alone, k_b, was determined by conducting a similar test in a clean, chlorine-consumption-free bottle. This test was repeated five times during the study period to observe any change in bulk rate constant. The k_b value was 0.28 day $^{-1}$ on average (standard deviation = 0.021 day^{-1}). The chlorine wall decay constant, k_w, is determined as the difference between the overall decay constant and the bulk decay constant.

Because chlorine reactions in pipes are affected by the nature of the compounds in the water and by temperature (Kiéné et al., 1998; Wable et al., 1991), the initial chlorine concentration (Hallam et al., 2002), and the mixing conditions (Rossman et al., 1994; Clark et al., 1995), all tests were conducted at constant room temperature, using the same water and a similar level of mixing, which is almost completely mixed, and all samples having the same initial chlorine concentration, thus ensuring consistent conditions not under study were consistent.

For determining the influence of the pipe service age on the effective first-order chlorine decay constant for chlorine consumption caused by the pipe material alone and avoiding the effect of biofilm, the internal surfaces of some of the pipe sections used in the study were brushed with a soft brush to remove most of the biofilm attached to the surface, if present, and the pipes were then rinsed and followed by the chlorine decay test described above. During brushing, care was taken to avoid disturbance of the internal pipe material.

3. Results and discussion

Chlorine decay at the pipe wall surface is a function of both mass transport of chlorine from the bulk liquid to the pipe wall surface, and the chemical reaction at, or with, the pipe wall surface. The value of the wall decay constant described above represents the effective decay constant (k_w), units 1/time. Such a constant is a function of the hydraulics, and the intrinsic wall decay constant (K_w), units of length per time (Rossman et al., 1994). The effective wall decay constant was also shown to be affected by the pipe size (e.g., Rossman et al., 1994; Haas et al., 2002; Menaia et al., 2003). The intrinsic wall decay constant can be determined from the effective wall decay constant using mass transfer equations appropriate for the hydraulics in the pipe reactor.

The intense mixing in the pipe section reactor ensures a continuous renewal of water at the pipe surface. This results in the elimination of the chlorine mass transfer resistance at the pipe wall and the following equation is applicable (DiGiano and Zhang, 2005):

$$\frac{dC}{dt} = -kC = -\left(k_b + \frac{K_w}{r_h}\right)C. \tag{3}$$

The second part on the right-hand side of Eq. (3) represents the effective chlorine wall decay constant. Therefore, Eq. (3) shows that the effective wall decay constant equals the ratio of the intrinsic wall decay constant (K_w) to the hydraulic radius (equals half of pipe radius if flowing full).

Since completely, or nearly completely, mixed conditions are intentionally made in the pipe reactors of this study, it can be assumed that hydraulic conditions are similar, and hence, for similar sizes, the only parameter changing with respect to the effective wall decay constant is the intrinsic wall decay constant. Therefore, it can be said that, for pipes of similar sizes, any observable differences with respect to pipe age can be inferred to result from changes in the intrinsic wall decay constant. The results presented in this study are being interpreted as "effective" first-order wall decay constant which would be dependent on the formulationused to represent the hydraulic mass transfer during wall decay processes; additionally the analysis will be performed on the same constant. It must be stated that without assuming any formulation regarding the impacts of hydraulic mass transport the results and analysis are not invalidated.

Significant chlorine consumption by some pipe wall sections was observed. The laboratory effective chlorine wall decay constants, k_w, of the 302 pipe sections ranged from 0.11 to 112 day^{-1}. Such a wide range of values was due to the variability in the pipe material, age, and size. According to the results, the wide variation found in the values of the chlorine wall decay constants proves that a single decay coefficient for all the pipes forming the distribution system, may not adequately predict residual chlorine at any point in the network as also indicated by Clark et al. (1994a).

Figs. 2 –9 illustrate graphically the effective chlorine first-order wall decay constants as a function of pipe service age for a variety of pipe diameters for different pipe materials.

For all pipe materials, the pipe service age was found to impact the wall decay constant, which indicates the condition of the internal surface material of the pipe changed with service time. Such a change varied with different pipe parameters, including the material used, and is expected to alter the chlorine consumption rate. The effect of pipe service age is quantified by comparing the value of the decay constant at a certain age with that of the corresponding recently installed pipes. As can be seen from the figures, wall decay constants either decreased (negatively affected) or increased (positively affected) with service age. For the range of the 55 years of pipe service age used in this study, wall decay constants ranged from a decrease by −92% to an increase by +431% from the corresponding values in the recently installed pipes.

Cast iron pipes (Fig. 2) were most affected by the positive effect of service age on the wall decay constants, whereas, steel pipes (Fig. 3) were less affected relative to cast iron. This could be justified as the increase in pipe service age results in corrosion of the internal surface of the pipe, hence more chlorine consumption. Both steel and cast iron unused pipes

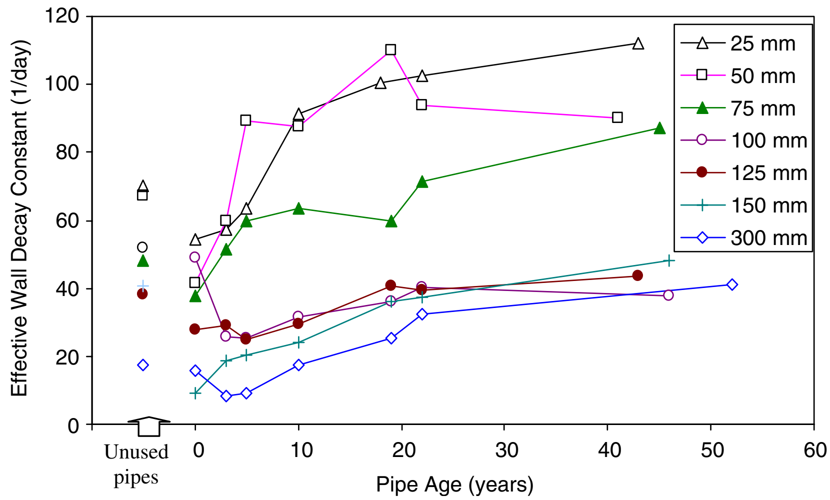

Fig. 2 – Effective first-order chlorine wall decay constants as a function of pipe service age for a variety of pipe diameters for cast iron pipe.

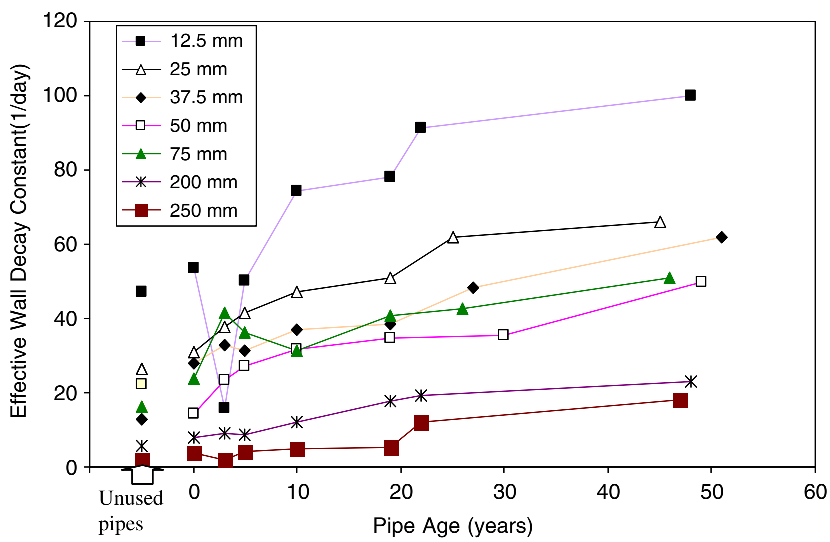

Fig. 3 – Effective first-order chlorine wall decay constants as a function of pipe service age for a variety of pipe diameters for steel pipe.

showed lower chlorine decay constants than those recently laid in the ground.

For pipe segments in the distribution system where the chlorine decay constant becomes high, it might be economical to replace it to avoid such a high chlorine demand and thus to meet water-quality goals. Clark et al. (1995) in their laboratory experiment on two galvanized-iron pipe sections, one brand new and the other 30–40 years in the ground, observed that chlorine was consumed in a few minutes in the old pipe, whereas, it remained stable over a 24-h period in the new pipe. Clark et al. (1994), in their simulation of the North Marin Water District network, observed that wall demand was highest for the oldest unlined cast-iron portion of the system.

CLCI (Fig. 4) and CLDI (Fig. 5) were less affected by service age than steel and cast iron. Both CLCI and CLDI exhibited similar patterns of response to the increase in pipe service age. With an increase in pipe service age, the chlorine wall decay constants decreased initially and then increased after a certain age; the change in the trend was approximately between 15 and 25 years of age. This suggests that in the early stages of pipe age, the cement layer works as an insulation layer protecting the iron from chlorine attack. However, this protective cement layer consumes chlorine but this consumption decreases with age as it becomes saturated with chlorine. Rossman et al. (2001) postulated the decrease of wall demand of unlined ductile iron over time by pipe acclimation to the chlorine or the depletion of the chlorine-demanding substances attached to the pipe wall. The positive effect of age beyond the inversion point could be justified as, after a certain period, the protection layer is corroded and the iron becomes exposed and starts to consume chlorine. This

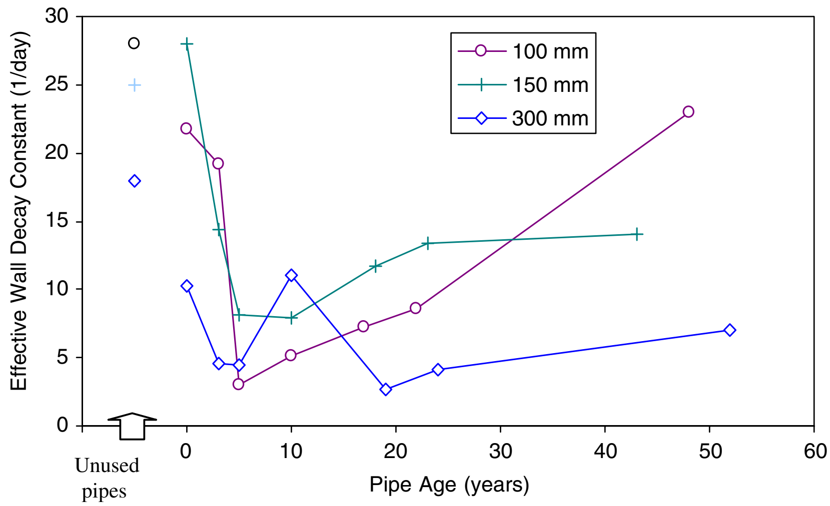

Fig. 4 – Effective first-order chlorine wall decay constants as a function of pipe service age for a variety of pipe diameters for cement-lined cast iron pipe.

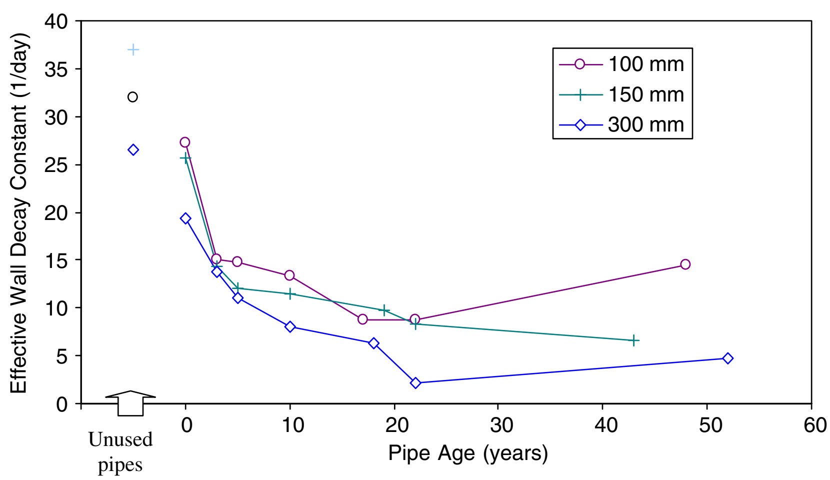

Fig. 5 – Effective first-order chlorine wall decay constants as a function of pipe service age for a variety of pipe diameters for cement-lined ductile iron pipe.

expected mechanism is a hypothesis and further investigations are needed to attest this. With an increase in age, the iron corrosion increases and hence chlorine consumption increases. Unlike cast iron and steel, recently installed CLDI and CLCI pipes showed lower chlorine wall decay constants than for corresponding unused pipes.

It can be inferred from Fig. 6 that, with the exception of the 200 mm pipes, the asbestos pipes exhibit a decreasing trend in the wall decay with service age. For all of the asbestos cement pipes, unused pipes showed higher values than the corresponding recently laid pipes.

As can be seen in Figs. 7–9, respectively, uPVC, PVC, and polyethylene pipes were affected negatively by pipe service age. This decrease in the wall decay constant was relatively low. A higher rate of decrease was observed during the first 3 years of usage. Polyethylene and uPVC pipes exhibited a relatively stable value over the remainder of the service age beyond the first 3 years. However, it should be noted that this stabilization in the decay constant value could occur before the first 3 years of usage. For all of these pipes, except the 100-mm (4-in) polyethylene, the chlorine wall decay constants of the unused pipes were higher than for all of those used. As there were no plastic-based pipes with ages greater than 25 years of age, available for this study, it should be noted that at ages greater than 25 years of age, an increase in the chlorine wall decay constant might occur, as was the case for the CLDI. The decrease of the chlorine wall decay constants from the unused pipes to the corresponding used pipes observed for these plastic-based pipes was not observed for the other materials tested in this study.

The results of this study are inconsistent with the results of Menaia et al. (2003) who concluded that the walls of new PVC pipes have no significant effect on chlorine consumption and assume that the same applies to all synthetic materials.

As can be noticed from the above findings, over time, some of the pipe materials illustrate an increase in wall decay constant and other pipe materials illustrate a decrease in wall decay constant. This interesting finding might contradicts

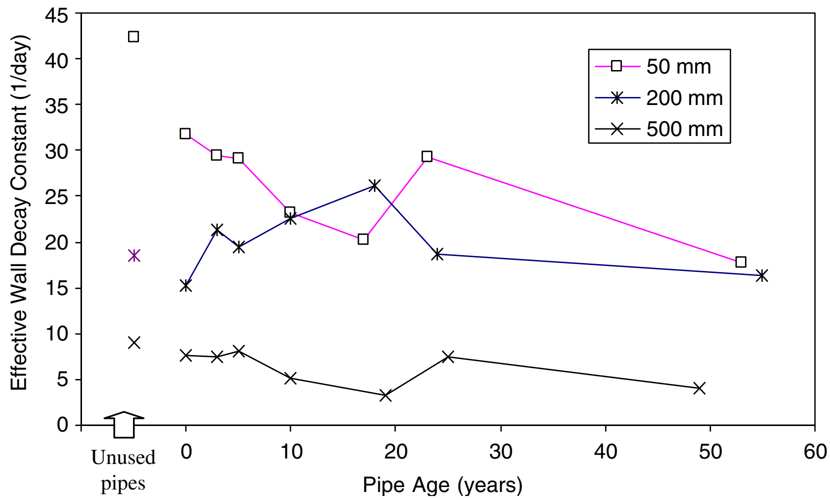

Fig. 6 – Effective first-order chlorine wall decay constants as a function of pipe service age for a variety of pipe diameters for asbestos cement pipe.

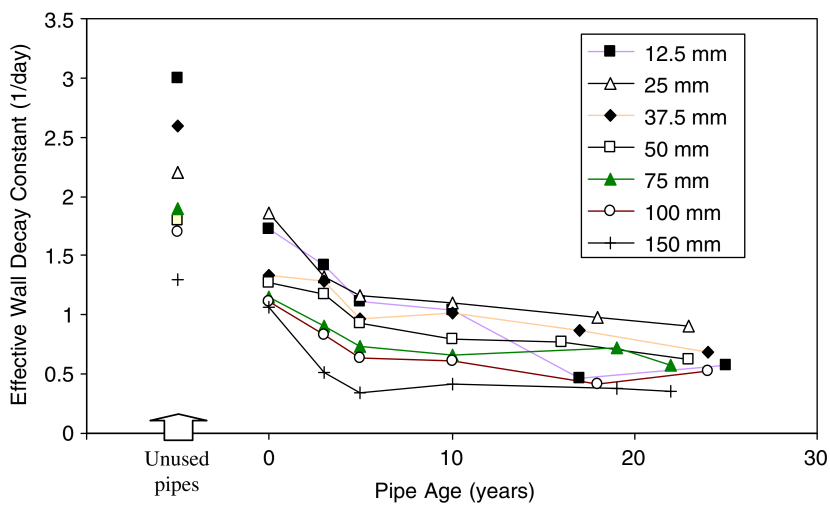

Fig. 7 – Effective first-order chlorine wall decay constants as a function of pipe service age for a variety of pipe diameters for uPVC pipe.

some expectations, and further researches might turn up some information related to why chlorine decay at the pipe wall increase/decrease over time.

With age, a biofilm layer may develop on the internal surface of the pipe. This layer may either create a chlorine demand or it may protect the internal pipe material from chlorine. Biofilm thickness is expected to increase with the increase of the TOC of the water as noted by Kiéné et al. (1998). According to the results of this research, the biofilm layer may be responsible for some chlorine consumption in a number of the pipes, thus, TOC may affects the chlorine wall decay constants. This is inconsistent with previous research conducted by Hallam et al. (2002) who pointed out that TOC had no influence on the chlorine wall decay constant, whereas it is consistent with that of Kiéné et al. (1998).

Because the biofilm layer varies depending on the characteristics of the water flowing into the system, it could be useful to explore chlorine consumption caused by the internal pipe material alone. Service age effect on the internal surface of the material alone cannot be explored directly as the development of tubercles and a biofilm layer would be expected to cause competing effects, increase and/or decrease chlorine consumption. Both the tubercles and the biofilm may consume the chlorine (Kiéné et al., 1998). Conversely, Hallam et al. (2002) suggested that the biofilm reduces chlorine consumption as it prevents chlorine penetration and reaching the pipe surface. Therefore, in this study, an attempt to explore the change with age of chlorine decay rate constant caused by the pipe material alone for some of the pipes which had been recently extracted from the distribution system was made. No research has been done to date on the effect of biofilm developed on internal pipe walls, as also pointed out by Hallam et al. (2002). A method was suggested as described in the materials and methods section, to avoid the effect of biofilm and determine the chlorine

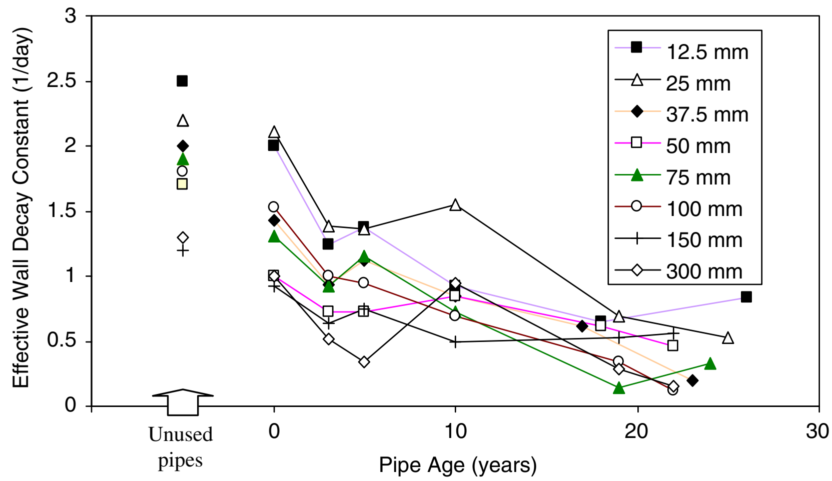

Fig. 8 – Effective first-order chlorine wall decay constants as a function of pipe service age for a variety of pipe diameters for PVC pipe.

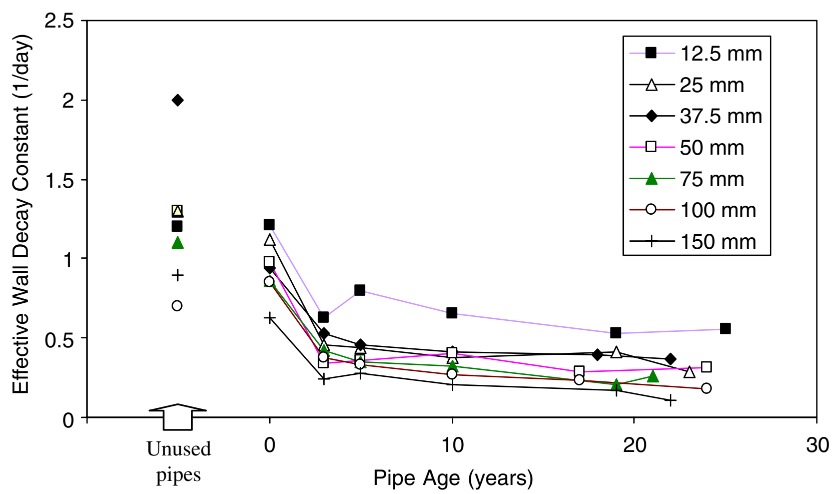

Fig. 9 – Effective first-order chlorine wall decay constants as a function of pipe service age for a variety of pipe diameters for polyethylene pipe.

consumption exerted by the pipe wall alone. The change in the effective first-order chlorine decay constant between and after brushing could be related to the biofilm.

With age, pipe material surface chemistry may change and contribute to chlorine consumption. The results showed that there is a decrease and increase in the new values from the corresponding chlorine wall decay constants. For medium age steel and cast iron pipes, around 18 years old, the removal of this layer caused a decrease of about 7% and 12%, respectively, whereas, for the old pipes it was noticed that constants increased by 15% and 18%, respectively. The decrease might be explained as the layer removed was consuming chlorine more than it was isolating the pipe material from consuming chlorine, whereas, the increase could be that the layer was protecting the material more than consuming the chlorine. For new steel and cast iron pipes, no significant difference was observed in the value of the decay constants. Both CLCI and CLDI iron pipes showed higher chlorine consumption rates when the layer was removed. This increase ranged from 3% to 12% of the corresponding pipes before removing the layer. This increase increases with pipe service age. No clear change for asbestos cement pipes was observed when such a layer was removed. A decrease was found for PVC, uPVC, and polyethylene pipes; however, this was insignificant. It must be also stated that using a soft brush could result in removing tubercles, or other oxidized surface material, that could expose additional pipe surface for reaction. As it was found in this research that cleaning the pipes with soft brush for removing the biofilm from the internal surface of the pipe does impact chlorine wall demand, the author would like to not place much emphasis on the mechanisms explained above as it is only a hypothesis. It is recommended to carry out further studies, of a similar or a modification to this method presented in the research, to establish the effect of the biofilm and tubercles formed on the pipe wall on the wall decay constant, as well as to understand the various mechanisms impacting wall demand.

Such an understanding of the variability in chlorine decay constant with service age helps in estimating the design age, and thus the suitability of the investment in replacing all or parts of the distribution system. Deposits in the field pipes also contribute to the chlorine demand (Kiéné et al., 1998); such an influence on chlorine consumption varies from one distribution system to another.

Variations of chlorine wall decay with pipe age can also help in assessing the effect of pipe age of the different pipes comprising drinking water distribution systems, on the fate of chlorine within drinking water distribution systems. This can be attained by using certain computer programs incorporating an appropriate chlorine mass transfer model. Rossman, et al. (1994) and Vasconcelos et al. (1996) incorporated a mass-transfer-based model into a computer program called EPANET. Different users (e.g., design engineers, water distribution system operators, maintenance workers, planners, and researchers) need these predictive models to design, manage, and study distribution networks. Such computer programs are useful for predicting water-quality degradation problems, calibrating system hydraulics, designing water-quality sampling programs, optimizing the disinfection process, evaluating operational and control strategies and storage reservoir design and operation of the distribution system, planning and designing of new systems, determination of problem areas or periods in the network, and sampling design for use in future water-quality monitoring.

4. Conclusions

Results of the experimental work performed on 302 pipe sections of different sizes, ages, and materials, led to several conclusions including:

1. Pipe service age is an important factor that should be considered in the consumption of chlorine in some pipes such as cast iron, steel, CLDI , and CLCI pipes especially when the bulk decay is not significant relative to the wall decay.
2. For the range of the 55 years of pipe service age used in this study, wall decay constants ranged from a decrease by −92% to an increase by +431% from the corresponding values in the recently installed pipes.
3. The positive effect of service age on the wall decay constant was the highest for cast iron pipes among the tested materials, whereas, steel pipes were less affected. Chlorine wall decay for CLCI and CLDI pipes was less affected by service age as compared to steel and cast iron pipes.
4. The chlorine wall decay constants of asbestos cement pipes were negatively affected by pipe service age.
5. The chlorine wall decay constants for PVC, uPVC, and polyethylene pipes were affected negatively by pipe service age. Age effect was relatively small.
6. Except steel and cast iron pipes, pipes not used before showed higher chlorine decay constants than those recently laid in the ground.
7. A wide variation in first-order chlorine wall decay constants was found ranging from 0.11 to 112 day^{-1}. Such a variation was due to the variation in pipe material, size, and service age.

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