

PIPE SERVICE AGE EFFECT ON WATER QUALITY IN DRINKING-WATER TRANSMISSION AND DISTRIBUTION SYSTEMS

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Abstract

Chlorination of water beyond the treatment plant is required for maintaining acceptable quality of water transported in the transmission and distribution system. 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. This varies with pipe parameters. The aim of this paper was to assess the impact of the service age of pipes on the chlorine wall decay constant. One hundred and fifty three pipe sections of different sizes and four 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. For the range of the 55 years of pipe service age used in this study, the change in the wall decay ranged from 8% to 531% of the corresponding values in the recently installed pipes. The effect of service age on the wall decay constants was most evident in steel pipes. Other important findings were reached.

Keywords: Water quality; chlorine wall decay constant, chlorine loss, distribution systems, transmission system, pipe service age.

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, the disinfectant should remain in the water flowing in the pipe as a detectable residual 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 ensuring that any likelihood of further contamination is eliminated. 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 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 needed for disinfection. Maul et al. (1985a) observed that there was a rapid decrease in both free and total chlorine residuals 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 disinfection of new pipes at high levels, as used in 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 concentration decreases 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 was observed to be in two phases (Zhang et al, 1992; Kiéné et al., 1998). The first phase occurs during the first 1 to 2 hours, or 4 hours (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:

$$\frac{dC}{dt} = -kC \quad (1)$$

where, dC/dt = rate 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 Equation 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:

$$C = C_0 e^{-kt} \quad \text{or} \quad \ln C = \ln C_0 - kt \quad (2)$$

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

DiGiano and Zhang (2005) concluded that a zero-order overall kinetic model is well suitable for describing the overall chlorine decay in a heavily tuberculated cast iron pipe, whereas, first-order overall kinetic model is found suitable for a new cement-lined ductile iron pipe.

The overall chlorine decay constant during the second phase is defined by AWWARF (1996) and used by researchers (e.g., Rossman et al., 2001, Hallam et al., 2002), to be the sum of the bulk decay constant, k_b , and the effective chlorine wall decay constant, k_w . Units of both constants are 1/time.

Chlorine wall decay were assumed (Wable et al, 1991; Biswas et al, 1993; Rossman et al., 1994; Clark et al., 1995; Ki  n   et al., 1998) and found to be characterized by first-order kinetics (Vasconcelos et al., 1996). Zero-order wall decay kinetic reaction was found by Vasconcelos et al. (1996) to be effectively characterizing the wall decay, however, he also pointed out that the first-order model might be better.

In this manuscript it will be assumed that the overall, bulk, and wall chlorine decay constants will be of a first-order kinetics.

Relatively few studies have been conducted concerning the determination of the chlorine disappearance rate in distribution systems. These works are 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 link, due to both the water and pipe consumption, can be determined using the above equation. This constant is described as the apparent or total 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, 25-mm (1-inch) 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 are similar. Rossman et al. (2001) performed tests in unlined ductile iron pipe loop to simulate field condition. 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). They investigate the effect of the velocity and the quality of water (corrosion rate, dissolved oxygen, and pH) on the decay rate of chlorine at the pipe wall of old cast-iron and new cement-lined ductile-iron.

Ki  n   et al. (1998) presented the relative importance of some parameters, namely, total organic carbon and temperature of the water, pipe material, biofilm, and corrosion, 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 surface of the pipe.

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 chlorine decay constant. Thus, this objective goes beyond the objectives of the previous studies.

MATERIALS AND METHODS

In order to accomplish the aim of this study, more than 185 pipe sections were collected. Out of these, 153 pipe sections were selected, prepared as described below, and used for performing the experimental work. These samples were either new (i.e. not used before), recently installed, or old pipes of different ages of usage in the 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 very small fraction (less than three percent) from well waters. The two sources are mixed together before it enters the network. New unused pipes will be referred to in the remaining part of this paper as unused pipes. To avoid dryness of the internal surface of the pipes, collected pipes were left in a tap water bath until the time of testing.

Four different pipe materials were used in the study, namely: steel, , , cement-lined ductile iron, polyvinyl chloride (PVC), unplasticized polyvinyl chloride (uPVC), and polyethylene. Pipes ages ranged from new to 55 years old. Pipes diameters ranged from 12.5 mm (0.5 inches) to 300 mm (12 inches). Old pipes were recently in service in a local distribution system.

All pipes were cut to a length of 1 m. Before performing the chlorine decay test, each pipe section was cleaned with tap water and mounted on a chlorine consumption-free glass sheet and sealed (Figure 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 (Ki  n   et al., 1998).

Pipe sections were randomly divided into 38 groups. Each group was tested over the same time period. 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.

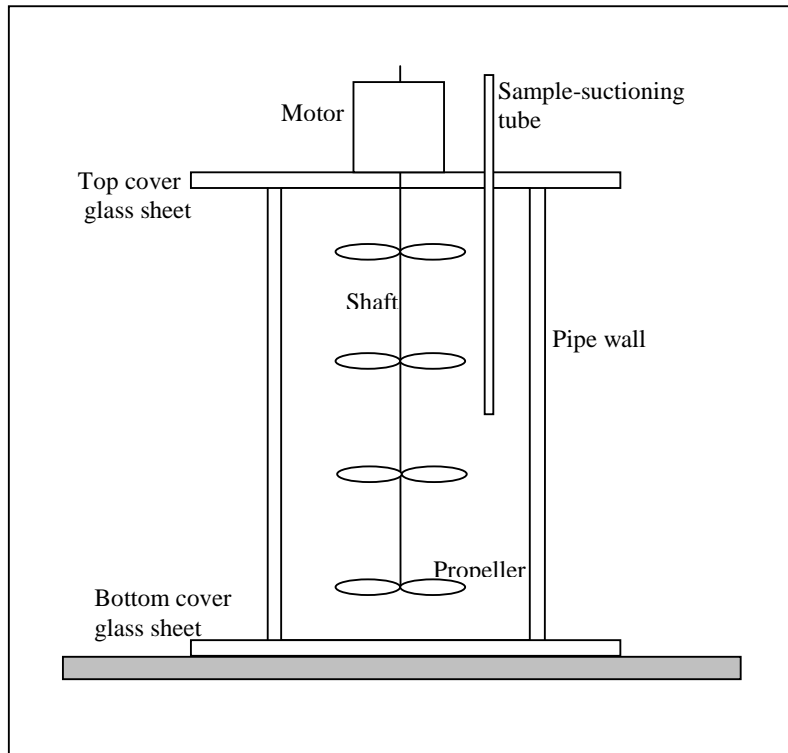


Fig. 1: Schematic of the experimental set-up

Chlorine decay tests were then carried out by filling the pipe section with chlorinated source water with an initial chlorine concentration of 2 mg/l. This water was first made of higher chlorine concentration and left for some time (about two hours) to avoid the first phase of chlorine demand, described in the introduction. 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 percent 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 the samples which are periodically withdrawn. The sampling program was stopped when the chlorine residual concentration became low, about 10 percent of the initial concentration; however, if this was not reached within three days, sampling was terminated. The maximum concentration at termination was 0.63 mg/l. For some of the pipe sections, the end point was reached after 30 minutes. The frequency of grab sampling was higher at the beginning and decreased gradually over time, ranging from one to ten minutes during the first hour and from one to four hours beyond the first hour during the first day, and from four to ten hours thereafter. Sampling frequency was adjusted so that the difference between any two consecutive concentrations is about 0.1 mg/l. Samples were tested directly after collection. Free residual chlorine concentrations were measured utilizing a Hach spectrophotometer, model DR-2010, and adopting 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 (Ki  n   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 concentrations, thus ensuring that all other conditions not under study were consistent.

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 is representing the effective decay constant (k_w), units $1/\text{time}$. 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 should 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):

$$\frac{dC}{dt} = -kC = k_b + \frac{K_w}{r_h} \quad (3)$$

The second part of the right hand side of Equation (3) represents the effective chlorine wall decay constant. Therefore, Equation (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.

From the experimental data it was found, as assumed, that the variations in the long-term overall chlorine concentration with time are best fitted by a first-order equation.

Significant chlorine consumption by some pipe wall was observed. The laboratory chlorine wall decay constants of 302 pipe sections ranged from 0.11 day^{-1} to 100 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, will not adequately predict residual chlorine at any point in the network as also indicated by Clark et al. (1994a).

Figures 2 through 5 illustrate graphically the variation in chlorine wall decay constants with pipe age.

For all pipe materials, the pipe service age was found to alter the wall decay constant. 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. This is expected to alter the chlorine consumption rate. The results were consistent with this expectation. It was found that the effect of pipe service age is best 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 55 years in pipe service age used in this study, the change in the decay constants ranged from 8% to 531% of the corresponding values in the recently installed pipes.

Among the four pipe materials steel (Figure 2) were most affected by the positive effect of service age on the wall decay constants. 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. 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. Unused steel pipes 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.

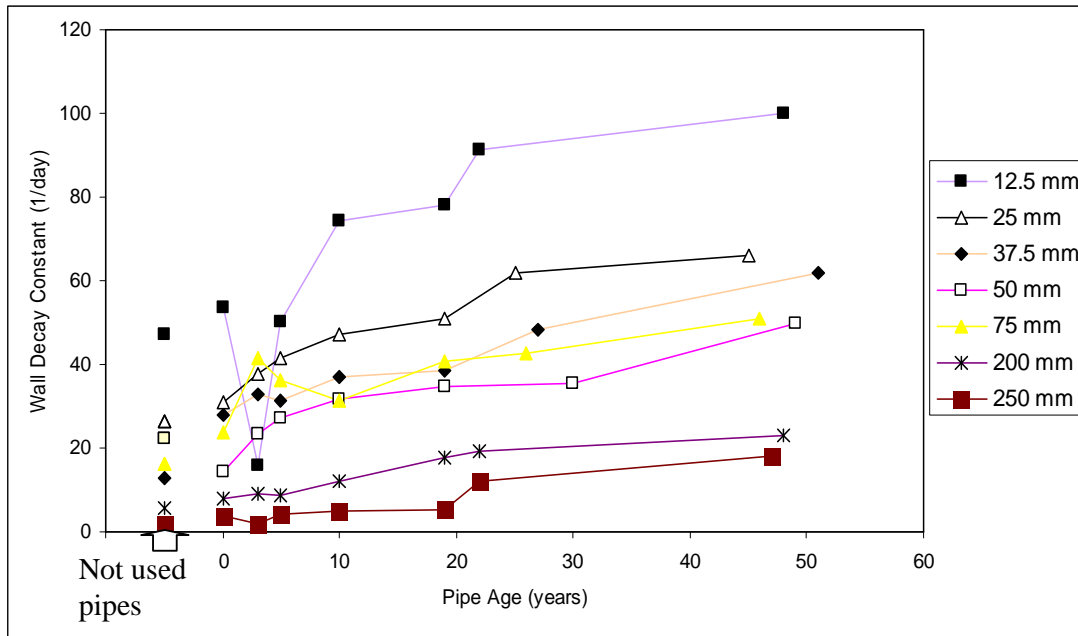


Fig. 2: Variation of chlorine wall decay constant with pipe service age for Steel pipes.

Cement-lined ductile iron (CLDI) (Figure 3) were less affected by service age than steel . CLDI exhibited similar patterns of response to the increase in pipe service age. Nevertheless, 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 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 steel, recently installed CLDI pipes showed lower chlorine wall decay constants than for corresponding unused pipes.

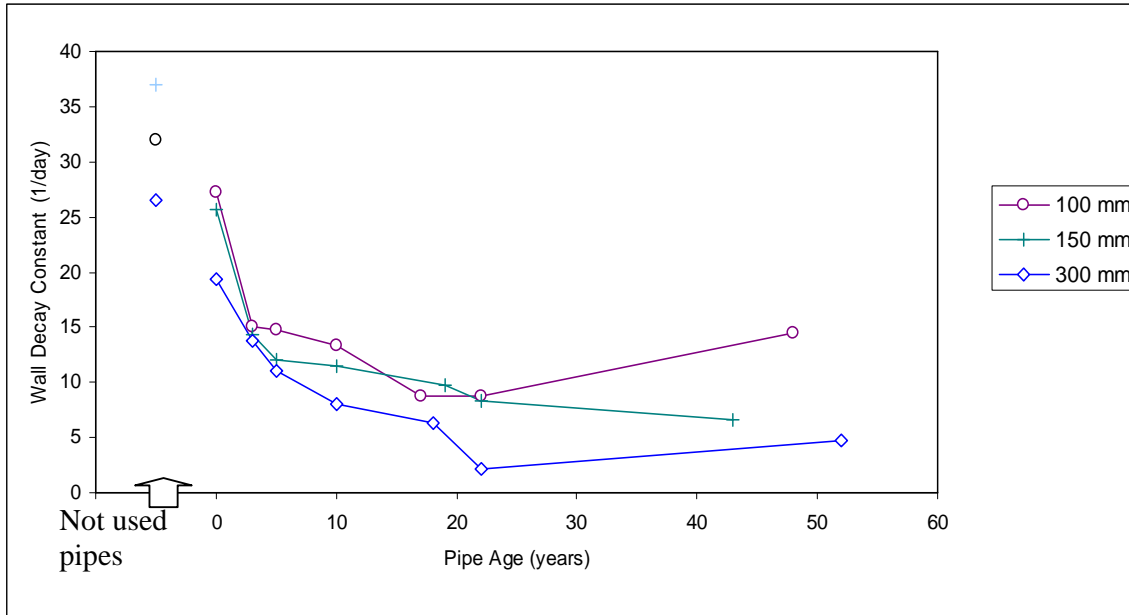


Fig. 3: Variation of chlorine wall decay constant with pipe service age for cement-lined ductile iron.

As can be seen in Figures 4, and 5, respectively, uPVC, , 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, the chlorine wall decay constants of the unused pipes were higher than for all of those used. This was not observed for the other materials tested in this study.

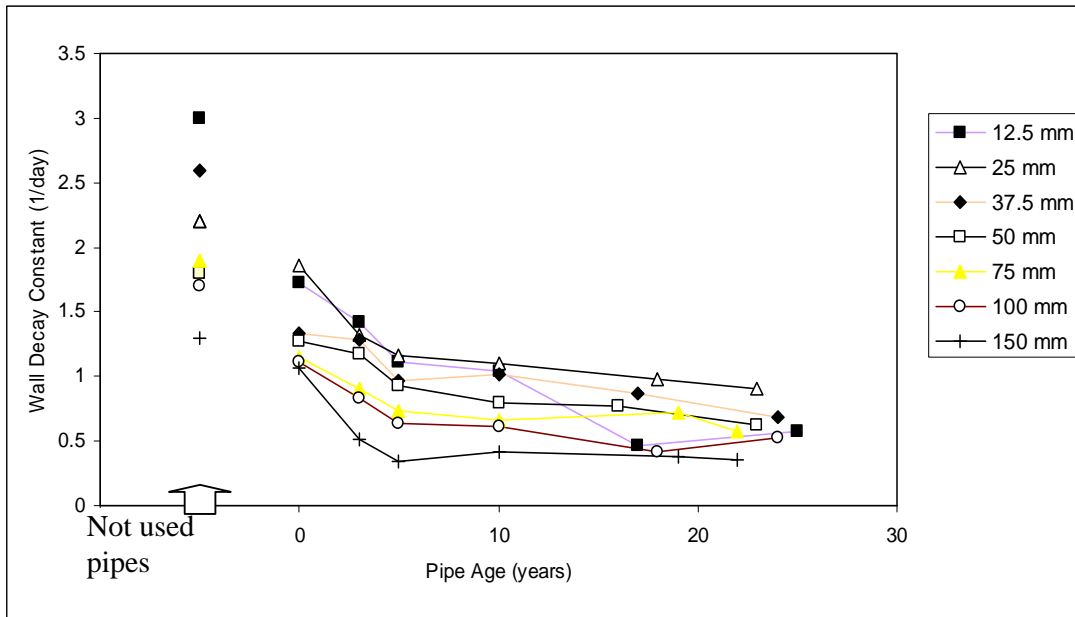


Fig. 4: Variation of chlorine wall decay constant with pipe service age for uPVC pipes.

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

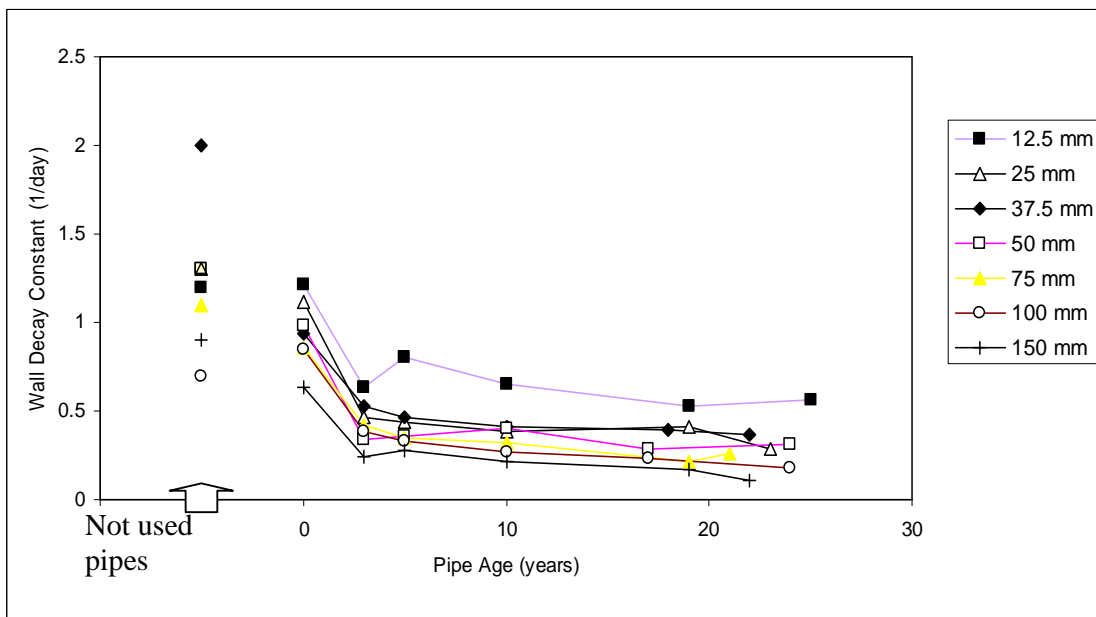


Fig. 5: Variation of chlorine wall decay constant with pipe service age for polyethylene pipes.

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 contradict some expectations, and further researches

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

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 was responsible for some chlorine consumption in a number of the pipes, Thus, TOC 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. However, the finding of this study is consistent with that of Kiéné et al. (1998).

Service age effect on the internal surface of the material cannot be explored directly as the development of tubercles and a biofilm layer would be expected to cause opposite effects – either increase chlorine consumption as the tubercles and the biofilm consume the chlorine (Kiéné et al., 1998), or reduce the wall consumption because the biofilm prevents chlorine penetration. Such an effect was also suggested by Hallam et al. (2002). Because the biofilm layer varies depending on the characteristics of the water flowing into the system, it could be useful to explore chlorine consumption by the internal pipe material alone. Therefore, in this study, chlorine consumption by the pipe material alone was explored in some of the pipes which had been recently extracted from the distribution system. 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). To avoid 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.

During brushing, care was taken to avoid disturbance of the internal pipe material. Brushed pipes were tested for chlorine decay. 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 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 pipes, no significant difference was observed in the value of the decay constants. Both and cement-lined ductile 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 pipes was observed when such a layer was removed. A decrease was found for, uPVC, and polyethylene pipes; however, this was insignificant. 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.

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 movement and

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) developed a mass-transfer-based model and incorporated it 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. Different applications were reported and include 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 (Clark et al., 1995), determination of problem areas or periods in the network, and sampling design for use in future water-quality monitoring.

CONCLUSIONS

Results of the experimental work performed on 153 pipe sections of different sizes, ages, and materials, leads 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 steel, cement-lined ductile iron pipes.
- 2- For the range of the 55 years of pipe service age used in this study, the change in the decay ranged from 8% to 531% of the corresponding values in the recently installed pipes.
- 3- The positive effect of service age on the wall decay constant was the highest for steel pipes among the tested materials. Chlorine wall decay for cement-lined ductile iron pipes was less affected by service age as compared to steel pipes.
- 4- The chlorine wall decay constants for uPVC, and polyethylene pipes were affected negatively by pipe service age. Age effect was relatively small. All sizes tested were affected by the pipe age with the same trend. (Pipe age effect did not show any effective relationship with pipe size).
- 5- Variation in the long-term chlorine concentration in pipes is best described by a first-order equation.
- 6- For all of the pipes tested, pipes not used before showed higher chlorine decay constants than those recently laid in the ground, whereas, this was the opposite for steel pipes.
- 7- A wide variation in first-order chlorine wall decay constants was found ranging from 0.11 day⁻¹ to 100 day⁻¹. Such a variation was due to the variation in pipe material, size, and service age.
- 8- For pipe segments in the distribution system where the chlorine decay constant becomes high, it could be economical to replace it to avoid such a high chlorine demand and thus to meet water-quality goals.

9- A standard method for determining chlorine wall decay constants in pipes should be used.

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REFERENCES

AWWARF (1996) Characteristics and Modelling of Chlorine Decay in Distribution Systems. USA: AWWA.

Biswas, P., Lu, C., and Clark, R. (1993) A Model for chlorine concentration decay in pipes. *Water Research* **27**(12), 1715-1724.

Clark, R.M. (1992) Water quality modelling in distribution systems. *Journal of Environmental Science and Health Part A*, **27**(5), 1329-1366.

Clark, R.M. and Coyle, J.A. (1990) Measuring and modelling variations in distribution system water quality. *Journal of the American Water Works Association* **2**(46), 46-53.

Clark, R.M., Goodrich, J.A. and Wymer, L.J. (1993) Effect of the distribution system on drinking water quality. *Journal of Water Supply: Research and Technology - Aqua* **42**(1), 30-38.

Clark, R.M., Smalley, G., Goodrich, J.A., Tull, R., Rossman, L.A., Vasconcellos, J.J. and Boulos, P.F. (1994) Managing water quality in distribution systems: simulating TTHM and chlorine residual propagation. *Journal of Water Supply: Research and Technology - Aqua*, **43**(4), 182-191.

Clark, R.M., Rossman, L.A. and Wymer, L.J. (1995) Modeling distribution system water quality: regulatory implications. *Journal of Water Resources Planning and Management* **121**(6), 423-428.

DiGiano, F., and Zhang, W. (2005) Pipe section reactor to evaluate chlorine-wall reaction. *Journal of the American Water Works Association* **97**(1), 74-85.

Haas, C.N., Gupta, M., Chitluru, R. and Burlingame, G. (2002) Chlorine demand in disinfecting water mains. *Journal of the American Water Works Association* **94**(3), 97-102.

Hallam, N.B., West, J.R., Forster, C.F., Powell, J.C. and Spencer, I. (2002) The decay of chlorine associated with the pipe wall in water distribution systems. *Water Research* **36**(14), 3479-3488.

Jadas-Hecart, A., El Morer, A., Stitou, M., Bouillot, P., and Legube, B. (1992) The chlorine demand of a treated water. *Water Research* **26**(8), 1073-1084.

Ki  n  , L., Lu, W. and L  vi, Y. (1998) Relative importance of the phenomena responsible for chlorine decay in drinking water distribution systems. *Water Science & Technology* **38**(6), 219-227.

Kirsch, B. Jr., Noble, T.C., Yu, C.H., Brazos, B.J. and O'Connor, J.T. (1994) Control of Microbial Water Quality in the Little Rock, Arkansas Distribution System. *Critical Issues in Water and Wastewater Treatment National Conference on Environmental Engineering*, ASCE, New York, 58-65.

Maul, A., El-Shaarawi, A.H. and Block, J.C. (1985a) Heterotrophic bacteria in water distribution systems: I. Spatial and temporal variation. *The Science of the total Environment* **44**, 201-214.

Maul, A., El-Shaarawi, A.H. and Block, J.C. (1985b) Heterotrophic bacteria in water distribution systems: II. Sampling design for monitoring. *The Science of the total Environment* **44**, 215-224.

Menaia, J., Coelho, S.T., Lopes, A., Fonte, E. and Palma, J. (2003) Dependency of bulk chlorine decay rates on flow velocity in water distribution networks. *Water Science and Technology: Water Supply* **3**(1-2), 209-214.

Rossman, L.A., Clark, R.M. and Grayman, W.M. (1994). Modelling chlorine residual in drinking-water distribution systems. *Journal of Environmental Engineering*, ASCE, 120(4), 803-820.

Rossman, L.A., Brown, R. A., Singer, P. C. and Nuckols, J. R. (2001). DBP formation kinetics in a simulated distribution system. *Water Research* 35(14), 3483-3489.

Vasconcelos, J.J., Boulos, P.F., and Clark, R.M. (1996) Kinetic models of chlorine decay in drinking water distribution systems. *Proceedings of the International Conference on Computer Methods in Water Resources, CMWR.*, Beirut, Lebanon, 413-421.

Wable, O., Dumoutier, N., Duguet, J.P., Jarrige, P.A., Gelas, G. and Depierre, J.F. (1991) Modelling chlorine concentrations in a network and applications to Paris distribution network. *Water quality modelling in distribution systems. American Water Works Association Research Foundation* 265-276.

Water Research Centre (1976) Deterioration of Bacteriological Quality of Water During Distribution. *Notes on Water Research No. 6*.

Zhang, G.R., Ki  n  , L., Wable, O., Chan, U.S., and Duguet, J.P. (1992) Modelling of chlorine residual in the water distribution network of Macao. *Environmental Technology* **13**, 937-946.