



THE IMPACT OF RESIDUAL CHLORINE DECAY ON WATER QUALITY IN A PIPED NETWORK - A LABORATORY SCALE TEST

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Abstract: The study aimed at assessing chlorine decay and its impact on water quality in the Kumasi Water Distribution Network, the second largest in Ghana. A Pilot Distribution System (PDS) was constructed with three different pipe materials excavated from the existing network; PVC pipes (15 - 20 years), Asbestos Concrete pipes (A.C., 40 - 50 years) and Cast Iron pipes (C.I., 84 years). The PDS was run with model water with two (2) predetermined residual chlorine concentrations of 0.74 mg/L and 1.44 mg/L. The loss in chlorine residual and the deterioration in water quality was assessed over a hydraulic retention time (HRT) of 24 hours.

Under the conditions tested, the C.I. pipes consumed chlorine faster possibly due to large encrustation on the pipe walls thereby compromising bacteriological safety of the water. Chlorine loss in cast iron pipes was also associated with pH drop, increase in colour and turbidity at $HRT \geq 2$ hours. For all pipes under test, microbial re-growth was observed after a HRT of 6 hours when chlorine concentrations are low. Nitrates were fairly constant with average concentrations of 2.29 mg/L and 2.51 mg/L respectively for AC and CI pipes. No direct correlation was observed between the trend in chlorine decay and that of calcium and magnesium ions. However, a rise in Fe and Mn concentration correlated positively with chlorine decay. Results show that during the first 2 hours where chlorine reacts rapidly with the bulk water and pipe walls, there was 73 % increase in the concentration of Fe and about 97 % increase in the concentration of Mn in Cast Iron pipes

Keywords: Chlorine decay, pipe walls, water quality

I. Introduction

One of the goals of a water distribution network is to deliver water at acceptable drinking quality. Water may be wholesome when it leaves the treatment plant, but its quality compromised through transformations within the distribution network^[3]. One of such transformations is the loss of disinfectant residuals which may compromise water quality by modifying the chemistry.

Chlorine is one disinfectant used to ensure bacteriological safety of drinking water. Usually residual chlorine is maintained within the distribution network to combat re-contamination of distributed water. To reduce the microbiological risk of potable water, it should have adequate disinfectant^[4]. In view of this, chlorine residual concentration between 0.20 - 0.5 mg/L is recommended by the WHO, and the Ghana Standard Authority guidelines recommend a concentration not lesser than 0.2 mg/L at the point of consumption^{[5][6]}. However, this residual decays in water due to reactions within the bulk water, between the bulk water and the pipe material or the bulk water and deposits on pipe walls^{[1][2][3]}. The rapidity of this decay and the extent of water quality deterioration depends on the type of pipe material, pipe age and hydraulic retention times. The study sought to use a pilot distribution system of three pipe materials to assess the possible impact of chlorine loss on water quality in the Kumasi Water Distribution Network (KWDN), the second largest in Ghana.

II. Study Area

The Kumasi Water Supply System currently consists of two treatment plants; the Barekese and the Owabi headworks. The Owabi headworks constructed in 1924 produces an average of 2.7 million gallons (MG) of treated water daily and the Barekese headworks which started operations in 1974, produces an average of 22 million gallons (MG) of treated water daily. Currently, chlorination is the disinfection method used in both headworks. Water supply to the main city centre is via the Barekese headworks^[6]. The KWDN has a total length of approximately 1,016,958 m and it comprises different pipe materials with the three most aged ones being Asbestos Cement (35%, 40 - 50 years), Polyvinyl chloride (48%, 15 - 20 years) and Cast Iron (5%, 84 years).

III. Experimental Design

Preparation of “Model” water

Model water was prepared (see Table 2) and used in the laboratory scale tests. The water simulated the characteristics of the final treated water at the Barekese Headworks. To achieve this, a five (5) year (2007-2011) water quality data of the finished water of the afore-mentioned headworks was obtained from the Ghana Urban Water Limited. The mean value per parameter was computed (see Table 1).

Table 1: Five year water quality data of the Barekese treated water

Parameter	Average value
pH	7.15
Temperature (°C)	26
Colour (HU)	5.4
Turbidity (NTU)	1.93
Residual chlorine (mg/L)	0.74
E-coli (No. /100 ml)	0
Hardness (mg/L)	63.40
Chloride (mg/L)	18.10
Total Dissolved Solid (mg/L)	67.27
Sulphate (mg/L)	35.79
Aluminium (mg/L)	0.11
Iron (mg/L)	0.20
Manganese (mg/L)	0.01
Fluoride (mg/L)	0.52
Nitrate (mg/L)	0.20
Arsenic (mg/L)	0.00

Source: Ghana Water Company Limited, Regional Water Quality Assurance Laboratory, Kumasi

Table 2: "Model" water characteristics

Parameter	Value
Temperature (°C)	26 - 30
pH	6.5 - 8.5
Free Chlorine Residual (mg/L)	0.74
Total iron (mg/L)	0.20
Manganese (mg/L)	0.01
Fluoride (mg/L)	0.52
Sulphate (mg/L)	36

After chlorination, a hydraulic retention time of thirty (30) minutes was normally allowed for bactericidal action on the model water just as it is done at the Barekese treatment headworks.

Pilot-scale tests

A Pilot Distribution System (PDS) was constructed such that two pipe materials under test could be fitted parallel to each other (see Figure 1). The pipe materials under test were PVC pipes (15-20 years old), Asbestos Cement pipes (AC pipes: 40-50 years old) and Cast Iron pipes (CI pipes: 84 years old). These pipe materials (all 6 inches in diameter) were part of existing service lines which were excavated from the Kumasi Water Distribution Network and each cut into three pieces of 1.0 m length. To determine the wall demand for each of the pipe material, two pieces (of length 1 metre) of each pipe type were connected in parallel within the PDS (Figure 1). The PDS was then flushed continuously under pressure of 0.5 bars with tap water for several hours to equilibrate the system and to obtain constant readings in terms of colour, turbidity, conductivity and TDS. After the first set of experiments, the third piece of each pipe material was connected in the PDS for another batch of tests with similar conditions to obtain triplicate sets of data for analyses.

The five (5) year water quality data obtained for the final treated water at Barekese headworks showed a mean free residual chlorine concentration of 0.74 mg/L. The first batch of chlorinated water was thus prepared to have an influent concentration of 0.74 mg/L. The concentration was then doubled for the second batch of chlorinated water to yield an influent chlorine concentration of 1.44 mg/L, with the intent of producing a doubled effect as that of the 0.74 mg/l. The first batch of chlorinated model water (0.74 mg/l residual chlorine) was fed into the PDS at 0.5 bars, and water samples were taken via sampling taps (taps A in Figure 1) to ascertain the residual chlorine concentration entering the pipe. Afterwards, the valves were closed so that the water stagnates in the test pipes. After a HRT of 2 and 4 hours, monitoring was done by periodic sampling at exit points of each of the 1.0 meter pipe lengths (taps B in Figure 1) and measuring residual chlorine concentrations and other physico-chemical parameters. After monitoring, the water was pumped out and pipes were refilled with chlorinated

water of same free residual chlorine concentration. The experiment was repeated for hydraulic retention times 6, 12, 18 and 24 hours and periodic monitoring conducted.

The pipes were then replaced with the last of the triplicate pipes and the experimental protocols above repeated. This first set of experiments was repeated for the three various pipe materials. After the first set of experiments, a second set of experiments with freshly prepared chlorinated water having free residual chlorine concentration of 1.44 mg/L was run at the various hydraulic retention times (as mentioned above) and monitored for the various pipe materials in triplicate.

To serve as a control, newer pipes for the PVC were obtained and used to run the experiments. However, for the AC and Cast Iron pipes, due to the unavailability of newer pipes, the encrustations in one of the 1 metre length pipe material was removed by mechanical means, washed thoroughly and used as a control. This is however a limitation to the work. It must be emphasised, that it was ensured that the internal chemical and physical structures of the pipe lines were maintained during excavation, transport, storage and assembling of the PDS. Also, before the test pipes were fixed in the PDS each time, it was ensured that newer PVC pipes were first fixed and the entire system was super-chlorinated and left to stand over-night to ensure that any possible residual microbe in the line is destroyed. Rigorous quality assurance and quality control were performed throughout the experiment on all pilot and laboratory test data.

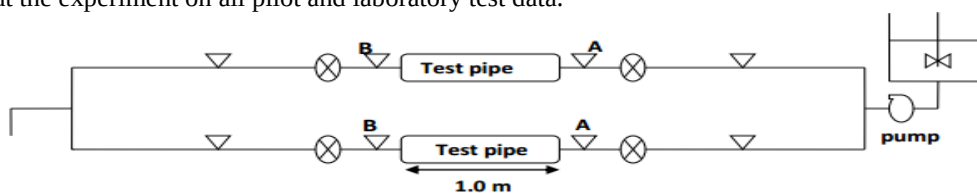


Figure 1. A Schematic Diagram of the Pilot Distribution System (PDS)

IV. Analytical Procedure

Table 3: Analytical methods

Parameter	Method
pH	Membrane probe
Temperature	Direct reading
Colour	Spectrometer
Turbidity	Spectrometer
Conductivity	Membrane probe
TDS	Membrane probe
Chlorine, residual	DPD colorimetric
Chlorine, total	DPD, colorimetric
Total iron	AAS
Manganese	AAS
Nitrate	AAS
Coliforms	Membrane filtration
E. coli	Membrane filtration
Salmonella	Membrane filtration

V. Results and Discussions

Chlorine Decay Pattern

Generally, free chlorine was observed to decay in three patterns; the first could be described as a more rapid decay which occurs within the first two hours of distribution where nearly over 50 % of the initial chlorine dose is consumed. This initial “heavy” demand could be attributed to the oxidation of some readily oxidizable ions such as Fe^{2+} , Mn^{2+} , S^{2-} and the reaction of free residual chlorine with biofilms and NOMs. The second pattern of decay, an “intermediate” one was observed to be relatively less rapid and occurred between 2 to 6 hours. The third pattern of decay was observed to be the slowest, and it occurred in situations where the free residual chlorine concentration was in trace amounts, usually below 0.1 mg/L.

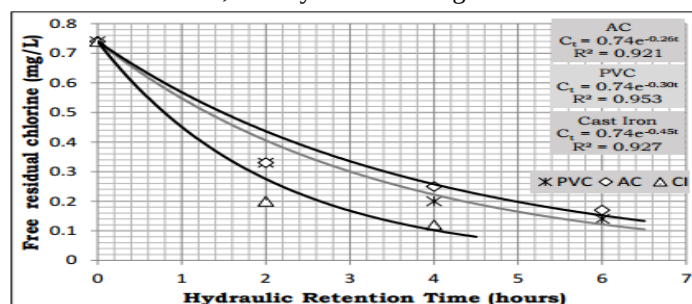


Figure 2: Trend in Chlorine residual decay observed for PVC, AC and Cast Iron pipe when influent concentration is = 0.74 mg/L

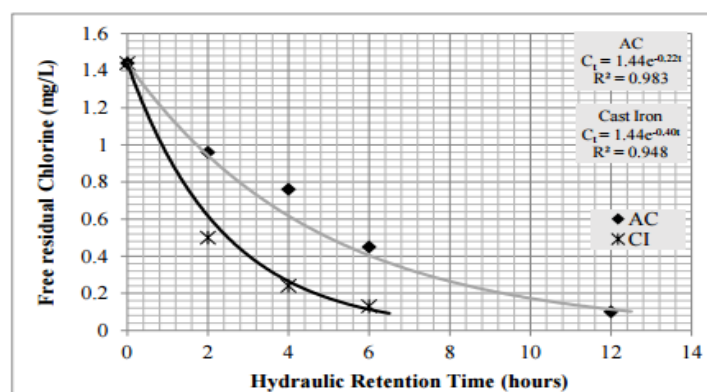


Figure 3: Trend in Chlorine residual decay observed for AC and Cast Iron pipe when influent concentration is 1.44 mg/L

pH

The pH represents the balance between hydrogen ions and hydroxide ions in water, and a unit change in pH represents a ten-fold change in the H^+ or OH^- concentration. For both the first and second batches of chlorinated water in the aged PVC and AC pipes, pH over the HRT of 24 hours was fairly constant ranging from a minimum of 6.7 to a maximum of 7.3. A similar trend was observed for the control pipes where pH values were fairly constant for the PVC pipe ranging from a minimum of 7.02 to a maximum of 7.30. These values were found to be within the GSA and WHO guideline value of 6.5 – 8.5. However, with the Cast Iron pipes, the pH ranges from a minimum 5.7 to a maximum of 6.9 for the aged pipe, and 5.20 to 6.9 for the control pipe. It was realised that pH drops to a value below 6.5 at a HRT ≥ 2 hours. This means that at a HRT ≥ 2 hours, water in the cast iron pipe becomes unwholesome with respect to pH. This decrease in pH with HRT could be attributed to an increase in H^+ ions in the water; as the water stagnates in the Cast Iron pipeline, there is more interaction between the chlorine and the encrustation (mainly made up of sand and organics like NOMs) deposited on the pipe walls. This interaction of chlorine with NOMs which usually proceed with a release of a proton or HCl tends to make the water acidic over time. Furthermore, adsorption of iron normally results in the release of protons and thus a drop in pH is expected. The pH associated with water in the cast iron pipes may also impart taste problems.

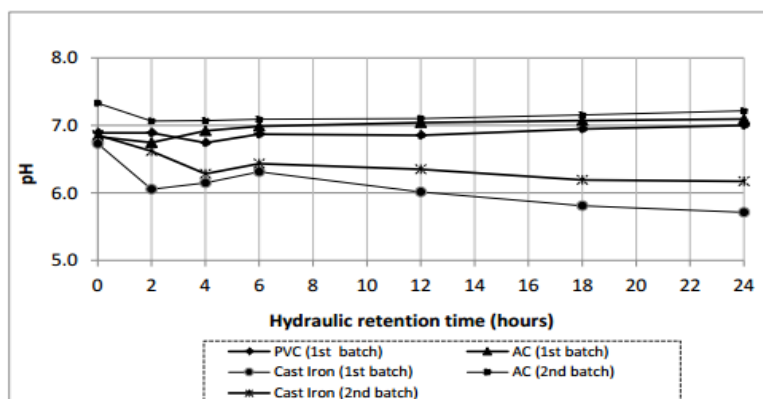


Figure 4: Trend in pH (Aged Pipes)

Colour

Colour in water may be of natural mineral or animal origin. It may be caused by metallic substances, humus material, peat, algae, weeds or protozoa. For all the pipe materials under study, colour was observed to increase with HRT. As oxidisable ions like Fe^{2+} and Mn^{2+} are oxidized to their +3 and +4 states respectively, the reddish brown colour of Fe^{3+} and the dark brown (or black colour) of Mn^{4+} is imparted to the water. Again the destruction of microorganisms by free residual chlorine also imparts colour to the water. It was observed that with higher initial free residual concentrations of 1.44 mg/L, the reactions proceeded faster within the AC and Cast Iron pipes with a corresponding release of higher colour. It was observed that, for the PVC and AC pipes, at a HRT ≥ 6 hours, the colour falls below the Ghana Standard Authority Guideline Value (GSA GV) of 15 Hazen Units. However for the Cast Iron pipes, it was observed that after a HRT of just 2 hours, the colour falls below the GSA GV. Increase in HRT of water in the Cast Iron pipes rose to 120 Hazen units which is about 8 times the GSA GV.

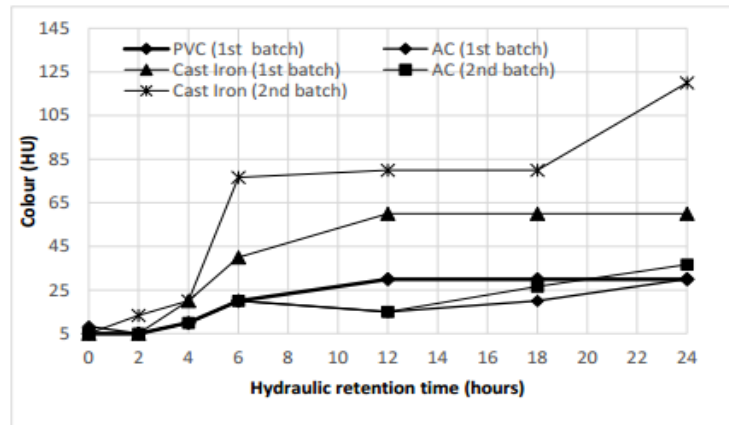


Figure 5: Trend in colour

Turbidity

Turbidity is a measure of water clarity (how far light can travel through water). The more particles suspended in a sample of water, the more difficult it is for light to travel through it and the higher the water's turbidity. The turbidity values correlated positively with colour for all pipes. As colour increased, there was a corresponding increase in turbidity; this increase could be attributed to the dissolved ions like Fe and Mn whose presence make water coloured and turbid. For the PVC and AC pipes, increase in turbidity values could be attributed to the oxidation of such oxidisable ions present in the feed water. It was observed that, the CI pipes recorded higher turbidity values as high as 24 and 28 NTU for the aged and control pipes respectively and these values do not fall within the GSA GV of 5 NTU. Higher Turbidity values may be as a result of the interaction of chlorine (which acts as an oxidising agent) with the pipe material, thus releasing Fe into the water. This higher turbidity may also be associated with lower oxygen levels thus making the water stale. In the case of the Cast iron pipes, lower pH favoured the solubility of the Ferric ion, thus imparting high turbidity to the water.

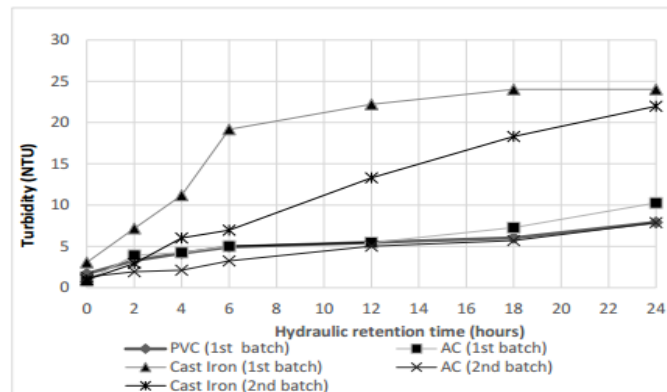


Figure 6: Trend in turbidity

Iron and Manganese

Lower pH favours the solubility of the Fe^{3+} and Mn^{4+} , thus imparting colour and turbidity. High concentrations of iron and manganese in drinking waters make the water aesthetically unpleasant for domestic and other use.

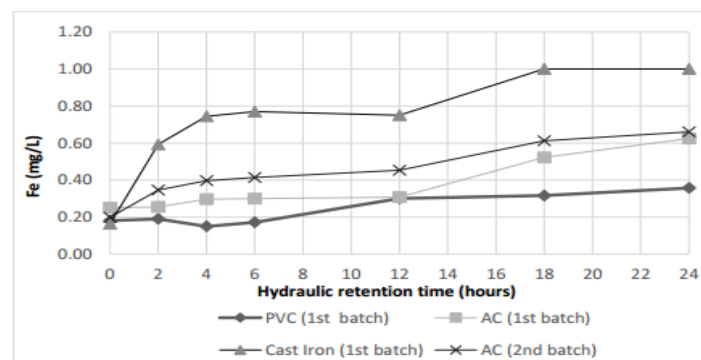


Figure 7: Trend in Fe concentration

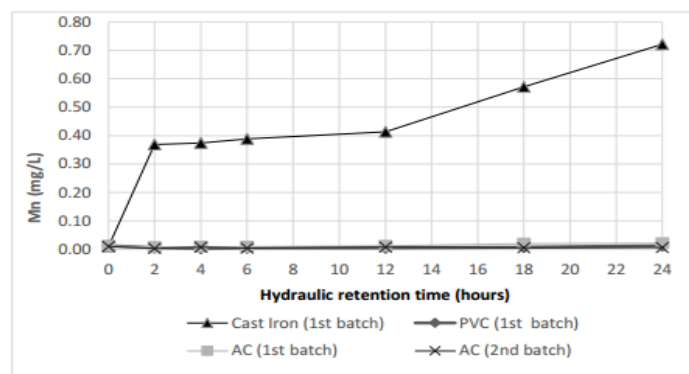


Figure 8: Trend in Mn concentration

For the PVC and AC pipes, Mn concentration was fairly constant (and same as the feed water) with both having an average concentration of 0.01 mg/L over a HRT of 24 hours. A similar observation was recorded for the control pipes of AC and PVC pipes which also had average Mn concentrations of 0.011 and 0.01 mg/L respectively. This implies that concentrations observed were entirely from the feed water and it clearly indicate that deposits (encrustation) observed in the aged PVC and AC pipes may have very negligible or no Mn deposits. However, these Mn concentrations were within the GSA GV and WHO guideline values. Averagely, Fe concentrations were also 0.24 and 0.4 mg/L for PVC and AC pipes respectively. This compares favourably with the observed average concentrations of 0.21 and 0.33 mg/L for PVC and AC control pipes respectively. This suggests that there may be negligible or no iron oxides deposited on the pipe walls of the aged PVC and AC pipes, thus concentrations observed were purely as a result of the presence of iron in the feed water. However, for the CI pipes, very high concentration of Fe and Mn were recorded. Average concentrations recorded for Fe and Mn were 0.72 and 0.41 mg/L respectively. The average Fe and Mn concentrations for the control pipes were also found to be 0.74 and 0.06 mg/L respectively. The equivalent values observed in terms of Fe concentration for the aged CI and control pipes suggest that the “large” encrustation on the aged CI walls may have formed a protective layer that prevented direct reaction of free residual chlorine with the walls of the pipe material to leach Fe from the walls of the pipe into the water. Rather, it is probable that the increase in Fe concentration observed over the HRT could be attributed to leaching of Fe from the Iron oxides already encrusted onto the pipe walls. These high concentrations corresponded with high colour (as high as 120 Hazen unit) and turbidity (as high as 24 NTU) values. This confirms that Fe and Mn could impart colour to water. Again, the rise in Fe and Mn concentration correlated positively with chlorine decay. Within a HRT of 2 hours, Fe concentrations exceeded the GSA GV and WHO guideline value of 0.3 mg/L. Similarly, Mn concentrations exceeded the GSA GV and the WHO guideline value of 0.4 mg/L. It was observed, that during the first 2 hours where the free residual chlorine reacts rapidly with the bulk water and pipe walls, there was about 73 % increase in the concentration of Fe and about 97 % increase in the concentration of Mn. This confirms that chlorine consumption in CI pipes could be attributed to the oxidation of the Fe and Mn deposits encrusted on the pipe walls. The increase in Mn and Fe concentrations correlated positively with acidity. As distributed water became more and more acidic (low pH in the CI pipes), the acidic medium favoured the leaching of Fe from the walls of the CI pipelines into the water and the dissolution of Fe and Mn. High levels of Mn recorded can be attributed to large deposits of Mn which was observed as black layers on the sediments (encrustation) in the lumen of the CI pipes, thus in the presence of strong oxidizing agents like chlorine, it reacts with the Mn deposits which in turn increases the concentration of Mn in the distributed water. This could be further explained with the variance in Mn concentration between the aged and control CI pipes which suggest that increase in Mn concentration was entirely due to Mn deposits in the encrusted material in the lumen of the CI pipe.

Again, it can be inferred that, Fe and Mn deposits form an appreciable quantity of ions in the encrustation observed in the lumen of the CI pipes. It is therefore not advisable to retain distributed water in the CI pipes for long hours as concentrations of these ions will increase over time. It is advised that supplies to areas where CI pipes dominate should be done during peak hours so that water does not stagnate in the pipe lines for longer hours. Also it will be advisable to regularly flush the CI pipes with high pressurized water to remove Fe and Mn deposits.

Calcium and Magnesium

Water that contain a significant concentration of dissolved minerals like calcium and magnesium are called “hard” and when hard waters are heated, they leave a mineral deposit called “scale.” Generally, calcium and magnesium concentrations were very low and within the GSA GV of 200 mg/L and 150 mg/L respectively and also within the WHO guideline value. Average calcium concentrations recorded were 14 mg/L, 16 mg/L and 16 mg/L for PVC, AC and CI pipes respectively. Similarly, average magnesium concentrations recorded were 8.97, 7.25 and 8.53 mg/L for PVC, AC and CI pipes respectively. It was observed that the trend in Mg concentration

was fairly constant for both aged and control pipes, but that of the calcium increased marginally over time. This slight increase especially for distributed water in the AC and CI pipes may be attributed to the cement lining in the case of the AC pipe and the sediments build-up (the sand component) in the CI pipes which may all be sources of calcium. However, there was no direct correlation observed between the trend in free residual chlorine decay and that of calcium and magnesium.

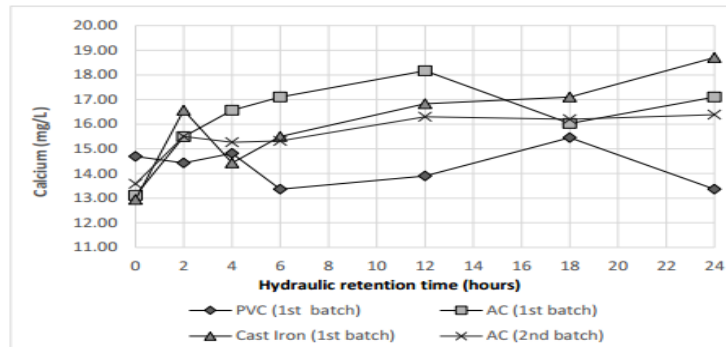


Figure 9: Trend in calcium concentration for aged pipes

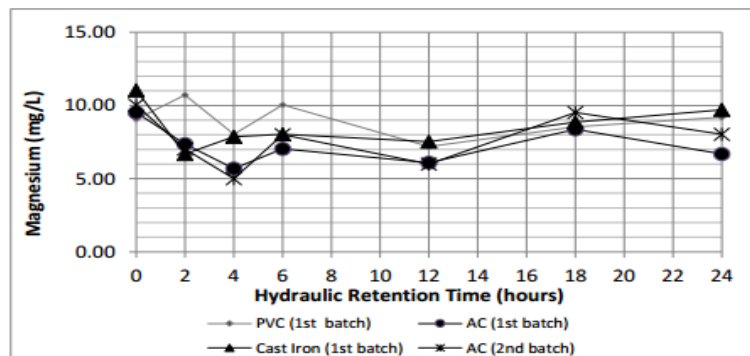


Figure 10: Trend in magnesium concentration for aged pipes

Nitrates

Once in water, nitrates can stimulate excessive plant and algae growth. For the PVC pipes, the relative increases in nitrate concentrations could be due to the organic coatings of the pipe material which could be a source of this nutrient. However, for the AC and CI pipes, a nearly constant trend was observed with average nitrate concentration of 2.29 mg/L and 2.51 mg/L respectively. Again, It was observed that within the first 6 hours where free chlorine consumption was high, there were increases in nitrate concentrations; this could be due to the fact that chlorine as an oxidant favoured the conversion of compounds like NH_3 to NO_2^- and then to NO_3^- . Again, for all pipes, in the event of trace residuals usually at HRT > 6 hours, there were significant drop in nitrate concentrations, this could be due to the fact that during anaerobic or anoxic conditions, NO_3^- reverts to NO_2^- . However, between HRT of 12 to 18 hours, an appreciable increase in NO_3^- concentration was observed. This could be associated with microbial or algae die-off which usually results in the release of NH_3 which subsequently is converted to NO_3^- . Furthermore there were no significant differences in nitrate concentrations between the aged and control pipes. Nitrate concentrations for all pipes under test was within the GSA and WHO guideline value of 50.0mg/L

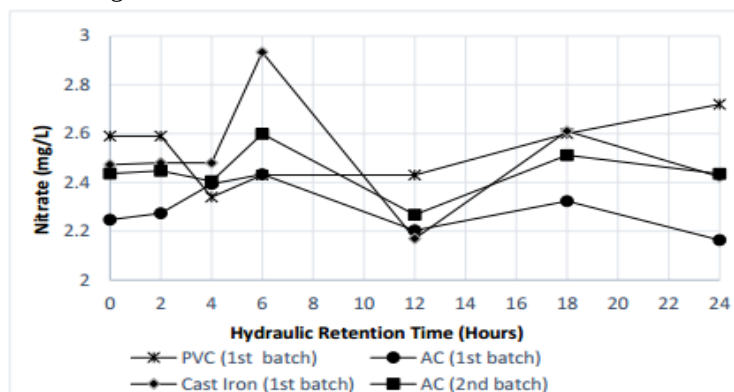


Figure 11: Trend in Nitrate Concentration for the aged pipes

Microbial quality

The presence of microorganisms may suggest the existence of a habitat that could be used by pathogens or the accumulation of chlorine-demanding material that interferes with maintaining a disinfectant residual throughout the pipe network. For the first batch of chlorinated water with influent free residual concentration of 0.74 mg/L, microbial growths were observed for the feed water after a HRT of 30 minutes. However, usually within 2 to 4 hours all microbes were observed to die-off. This may suggest that at optimum pH, a HRT of 30 minutes may not be sufficient for 100 % bactericidal effect for chlorinated water with influent free residual chlorine concentration ≤ 0.74 mg/L, but rather this could be achieved between HRT greater than 30 minutes to a maximum of 4 hours.

However, for the feed water with initial free residual chlorine concentration of 1.44 mg/L, no growths were observed. This means that after a HRT of 30 minutes, chlorinated water with free residual chlorine concentrations ≥ 1.44 mg/L may not support the survival of microbes.

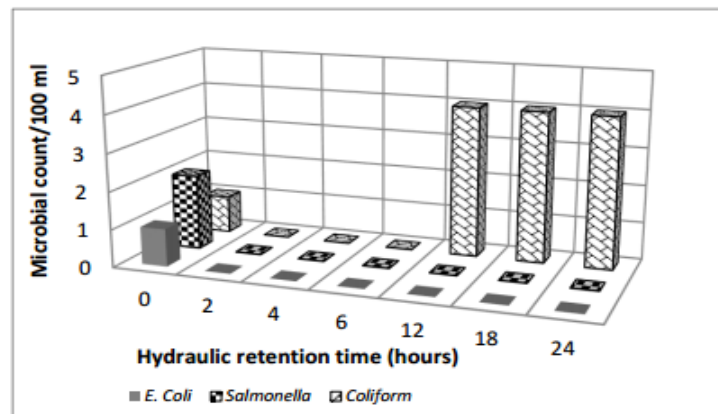


Figure 12: Trend in microbial growth observed in PVC pipes (1st batch)

For the PVC and CI pipes, after a HRT of 6 hours where trace residuals were recorded, *Coliform* growths were observed and this could be due to the presence of biofilm on the pipe walls. The presence of these biofilm resulted in the re-growth of the microbes in limited amounts of chlorine.

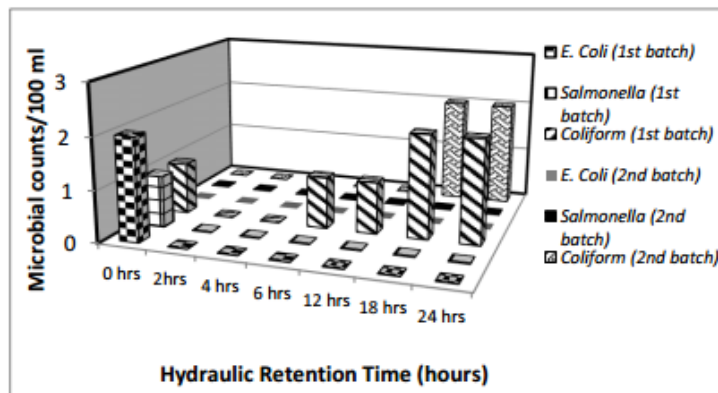


Figure 13: Microbial growth observed for the aged AC pipe

With the CI pipes, negligible microbial growths were observed after 6 hours for the first batch of chlorinated water (influent concentration 0.74 mg/L); this hour marks the start of a pH drop ($\text{pH} \leq 6$) in the CI pipe, thus it may suggest that although there were trace free residual chlorine concentrations in the water, the acidic nature of the water did not support the metabolism of the microbes, thus lower counts were observed in the CI pipes. However, for the second batch of chlorinated water (influent concentration of 1.44 mg/L), few microbial counts were associated with trace free residual chlorine, this could be due to the fact that the pH of the water (≥ 6.2) favoured the metabolism of the microbes. Furthermore, microbial growths observed in the control pipes were relatively lesser than that of the aged pipes. This could suggest that the presence of biofilms in the aged pipe contributed to relatively higher microbial growths observed. In addition, no microbial growth were observed when influent free residual concentration of the control pipes was 1.44 mg/L and this could mean that ideally for newer pipes, such a concentration may prevent re-growth of microbes.

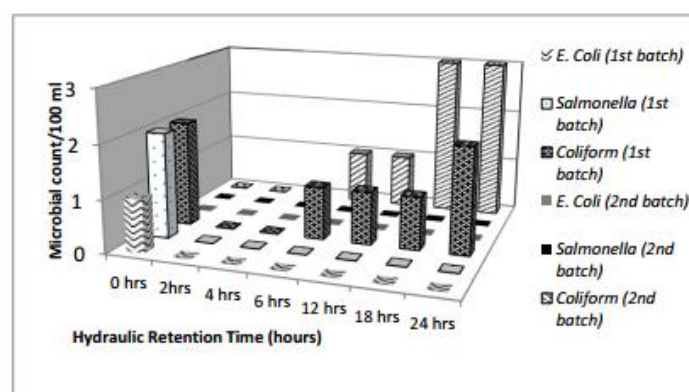


Figure 14: Trend in Microbial growth observed in aged CI pipes

VI. Conclusion

Cast Iron pipes were found to consume chlorine faster due to large encrustations possibly leading to increased wall demand. Chlorine decay was associated with pH drop and an increase in colour and turbidity in the Cast Iron pipes. Similarly, reduction in chlorine residuals correlated with an increase in Fe and Mn concentrations. This may present taste and odour problems to consumers. Water may also be aesthetically objectionable and may stain clothes. For all pipes under test, microbial re-growth was observed after a hydraulic retention time of six hours when chlorine concentrations are low.

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