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The Influence of Cement Mortar Lining Deterioration on Water Quality in a Simulated Reclaimed Water Distribution System

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Abstract. In this paper, the chemical and microbial erosion effects of reclaimed water on cement mortar lining in a simulated distribution system were investigated. Regular monitoring for the effluent pH, metal ions, nutrients and microbial biomass were conducted. Moreover, X ray diffraction (XRD) analysis for cement mortar lining were also tested to discuss the cement mortar lining deterioration. The results showed that reclaimed water was easy to breed microorganisms during transportation and distribution and had strong corrosion effect for cement mortar lining. The erosion of hydration products in cement mortar and the leakage of those components increased the concentration of effluent pH and metal ions, which would affect the reuse of reclaimed water.

1. Introduction

Reclaimed water refers to the non-potable water which can be recycled in a certain range after the sewage is purified by appropriate technologies to meet specified water quality and safety requirements [1]. Reclaimed water can not only effectively mitigate the resource-based and pollution-induced water shortage in China, but also reduce or avoid the damage of pollutant emissions to surface water [2]. Reclaimed water has been widely used in gardens, green space and farmland irrigation, landscape water, industrial cooling water and many other fields. However, reclaimed water is acquired from sewage plant effluent, so reclaimed water may contain higher concentration of suspended solids, organic matter, salinity and pathogenic microorganisms, etc. [3]. Therefore, reclaimed water having poor chemical and biological stability will react with the pipe material in transportation network. These complex reactions may not only affect the reclaimed water quality, but also corrode pipe material even affecting the safety of distribution system [4]. Cement lining ductile iron pipe is widely used in various water pipeline networks because of its stable mechanical properties, good durability and cheap price. However, many studies have shown that cement-based materials would degrade after acids, alkaline, organic matters, inorganic substances or microorganisms' corrosiveness [5]. Zhang had found that reclaimed water had erosion effect on cement mortar [6]. Wen investigated the corrosion mechanism of various factors in sewage system for concrete, and found that the super imposition effect of concrete corrosion, i.e., the corrosion effect of individual factors such as salt or microbial corrosion is less than those of various factors [7].



This study used HPC, XRD and water quality monitoring results to investigate the corrosion effect of reclaimed water on cement mortar lining of newly purchased pipe, the change of key water quality indexes of effluent in system, the change of cement mortar lining composition, and the influence of cement mortar lining corrosion on the water quality of the system.

2. Materials and Methods

2.1 Pipe loop set-up and experimental operation

The simulated reclaimed water distribution system consists of three 1 m-length DN100 new cement mortar lined ductile iron pipe sections, the water tank, metering pump and flow meter connected by PVC plastic pipe (DN20) to form a recirculating pipe rig system (figure 1). Reclaimed water was circulated from the water tank to testing loops using a metering pump at flow rate of $4 \text{ L} \cdot \text{h}^{-1}$ with the hydraulic retention time of 16h. There was no disinfectant added during the experimental period. Effluent water quality indexes were determined, and cement mortar lining coupons were also taken out and tested for the changes of its composition at regular intervals.

2.2 Experimental water

The reclaimed water used in the system was taken from a water reclamation plant in an northern city of China from December 2014 to June 2015. The threshold values of the monitored parameters were summarized in Table 1. The evaluation indexes for chemical stability of reclaimed water (Langelier Saturation Index (LSI), Ryznar Stability Index (RSI) and Aggressive Index (AI)) were calculated according to the monitored water quality parameters, as shown in table 1.

Table 1. Water quality parameters of reclaimed water (units: conductivity in $\mu\text{S} \cdot \text{cm}^{-1}$, alkalinity in $\text{mg} \cdot \text{L}^{-1}$ as CaCO_3 , others in $\text{mg} \cdot \text{L}^{-1}$).

pH	turbidity	TDS	COD _{Cr}	TN	TP	Cl ⁻	SO ₄ ²⁻	free chlorine
6.59-7.13	0.24-0.54	571-625	9.1-32.7	11.5-14.7	0.04-0.32	181-245	132.5-222.6	0.2-4
NH ₄ ⁺ -N	alkalinity	Ca ²⁺	Al	Si	Mg ²⁺	Langelier	Ryznar	AI
0.07-4.6	0.2-0.3	42.8-77.5	0-0.08	0.07-3.6	0-11.2	-1.83-0.88	8.9-10.26	10.07-11.02

2.3 Analytical methods

2.3.1 Test method for Water quality index. The pH, DO and conductivity were measured using Portable Multiparameter meter (HQ30D HACH, USA) and the turbidity was measured using a 2100P Turbidimeter (HACH, USA). The Si, Al, Ammonia-N, TN, TP and COD_{Cr} were measured using PE UV/Vis Lambda35 spectrophotometer. The TOC was measured using TOC-VCPH Analyzer (SHIMADZU, Japan). Alkalinity were measured by chemical titration. The sulfate and chloride were analyzed by Ion Chromatography System-1500 (Dionex, USA). The Ca²⁺ and Mg²⁺ were analyzed by the Atomic Absorption Spectrometer (Perkin-Elmer AAnalyst400, USA). Water quality was measured according to Standard Methods [8]. Heterotrophic plate counts (HPC) was used to enumerate cells of effluent at different experimental period in the system. .

2.3.2 Composition analysis of cement mortar. The XRD (D/max-rA, Rigaku, USA) operation parameters were: Cu K α radiation at 40KV and 100mA, the 2 θ ranged from 3°C to 70°C with a 0.02°C step, and a 0.15s count time at each step. Crystalline phase was identified using the Jade XRD software, and crystalline phase composition of the cement-mortar liner was quantitatively determined by contrasted parameters of intensity method [9].

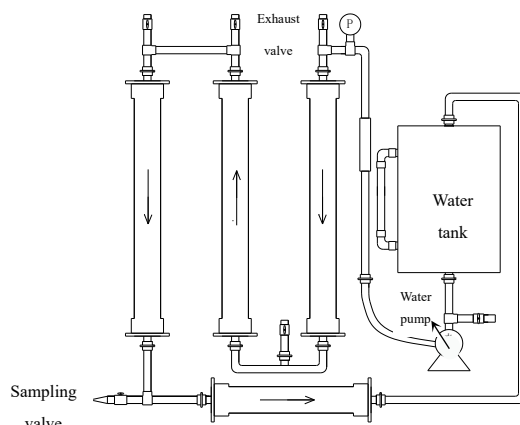


Figure 1. Simulated reclaimed water distribution system used for experiment.

3. Results and Discussion

3.1 Characteristics of effluent water quality of simulated reclaimed water distribution system

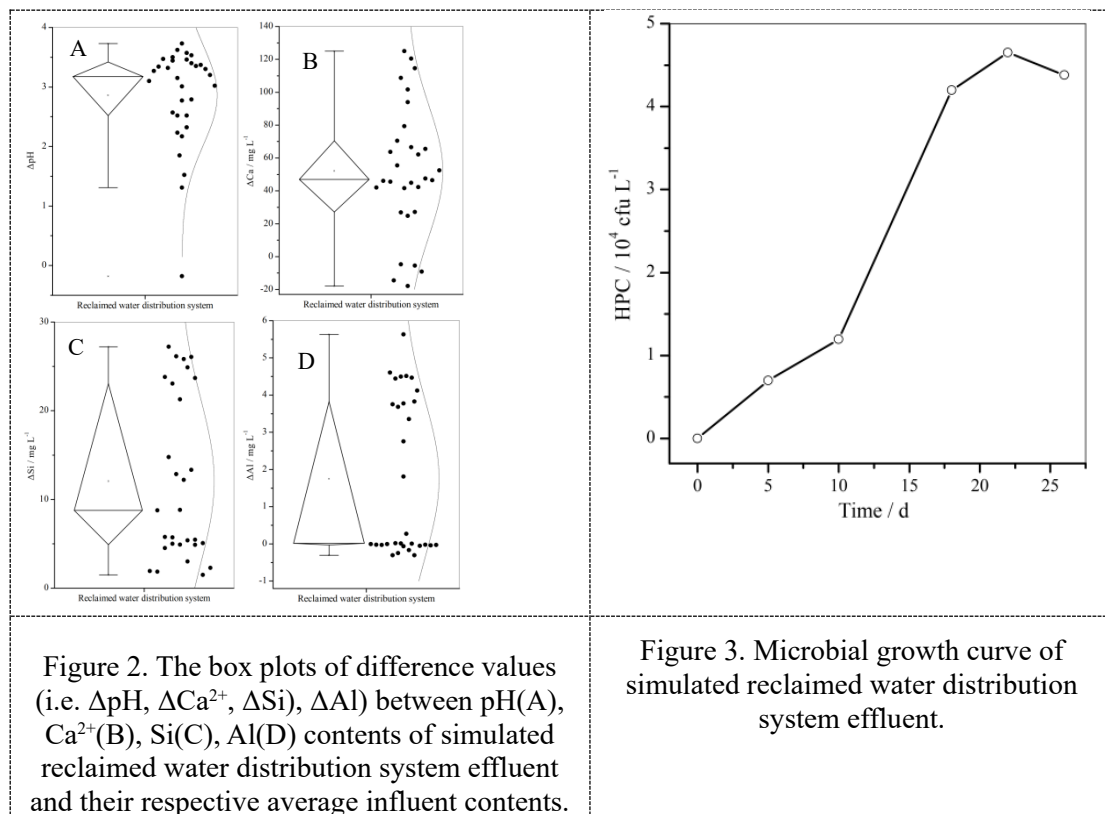
The concentrations of the major water quality indexes of reclaimed water were higher than those of tap water, such as alkalinity, hardness and other ions (Cl^- , SO_4^{2-}) (table 2). From its values of LSI, RSI and AI, it can be estimated that the reclaimed water had medium or strong corrosiveness for cement-based or metal-based materials.

The pH values of influent were 6.59-7.13. The pH value increment (ΔpH) of the system effluent were -0.18-3.73, and the mean value of effluent pH was 2.86 (figure 2). The Ca^{2+} values of the influent were 42.8-77.5 $\text{mg}\cdot\text{L}^{-1}$. The effluent ΔCa^{2+} values were -17.92-125.03 $\text{mg}\cdot\text{L}^{-1}$, and the mean value of effluent Ca^{2+} was 52.08 $\text{mg}\cdot\text{L}^{-1}$. The Si value of influent were 0.07-3.6 $\text{mg}\cdot\text{L}^{-1}$. The system effluent ΔSi were 1.48-27.21 $\text{mg}\cdot\text{L}^{-1}$, and the mean values of effluent Si was 12.06 $\text{mg}\cdot\text{L}^{-1}$. The Al value of influent were 0-0.08 $\text{mg}\cdot\text{L}^{-1}$. The system effluent ΔAl were -0.31-5.63 $\text{mg}\cdot\text{L}^{-1}$, and the mean values of effluent Al was 1.75 $\text{mg}\cdot\text{L}^{-1}$. Due to the erosion of cement mortar liner, many alkaline components were leaked into the water, so the pH values and the concentrations of effluent Ca^{2+} , Si and Al all increased during the experimental period.

3.2 Changes of effluent microbial biomass and its related water quality index

Microbiological growth curve of the effluent water in the system (figure 3) showed that the microorganism undergone a acclimation phase, logarithmic growth phase, stationary phase and endogenous respiration phase within a month. The HPC counts in 5d, 10d, 18d, 22d and 26d were 700, 1.2×10^4 , 4.2×10^4 , 4.7×10^4 , $4.4\times 10^4\text{cfu}\cdot\text{L}^{-1}$. Indicators closely related to microbial growth: effluent ΔTOC , ΔTN , ΔTP and $\Delta\text{NH}_4^+\text{-N}$ values variation were in figure 4.

The ΔTOC , ΔTN of effluent were -0.98-1.77 $\text{mg}\cdot\text{L}^{-1}$ and -0.7-14.14 $\text{mg}\cdot\text{L}^{-1}$, respectively. The mean values of effluent TOC and TN were lower than those of their influent values. So the TOC and TN of system effluent decreased from their whole value range and mean values which indicated the microbial propagation consumed a certain amount of TOC and TN. The effluent ΔTP and $\Delta\text{NH}_4^+\text{-N}$ were -0.04-(-0.13) $\text{mg}\cdot\text{L}^{-1}$ and -1.41-(-1.6) $\text{mg}\cdot\text{L}^{-1}$, respectively. The mean values of TP and $\text{NH}_4^+\text{-N}$ were -0.1 $\text{mg}\cdot\text{L}^{-1}$ and -1.58 $\text{mg}\cdot\text{L}^{-1}$, respectively. TP and $\text{NH}_4^+\text{-N}$ were also essential nutrients for microbial growth. To sum up, the reclaimed water with poor biological stability is easy to breed microorganisms during network transportation, and microbial metabolites can lead to cement mortar aggregate leakage resulting in cracking and internal metal rust [5].



3.3 Deterioration of cement mortar lining

The surface layer sample of cement-mortar liner was the top layer with 2-3mm thickness scraped off by a spatula and the rest of cement-mortar liner was the inner layer sample. They were separated and analyzed by XRD respectively. X-ray diffraction analysis (XRD) (table 2 and figure 5) showed that the content of crystalline $CaCO_3$ in the cement mortar lining tends to increase with the increase of test time, and surface layer was all carbonized to $CaCO_3$. The contents of the original hydration products $Ca(OH)_2$, Ca_3SiO_5 , Ca_2SiO_4 and $Ca_2(Al,Fe+3)_2O_5$ in the liner were reduced from 15%, 10%, 16% and 19% to 8%, 8%, 6% and 8%, respectively. In addition, SiO_2 , Albite and Microcline are the components of gravel in cement mortar liner. With the experiment proceed, carbonization of the lining surface may be the surface deposited reaction of Ca^{2+} lost from liner with CO_3^{2-} or HCO_3^- ions in water, or may be the microbiologically induced calcite precipitation (MICP)[10]. The content of hydration products with dense structure and high strength were decreasing, and many components such as: Ca^{2+} , Si and Al were dissolved, leading to loose cement liner structure.

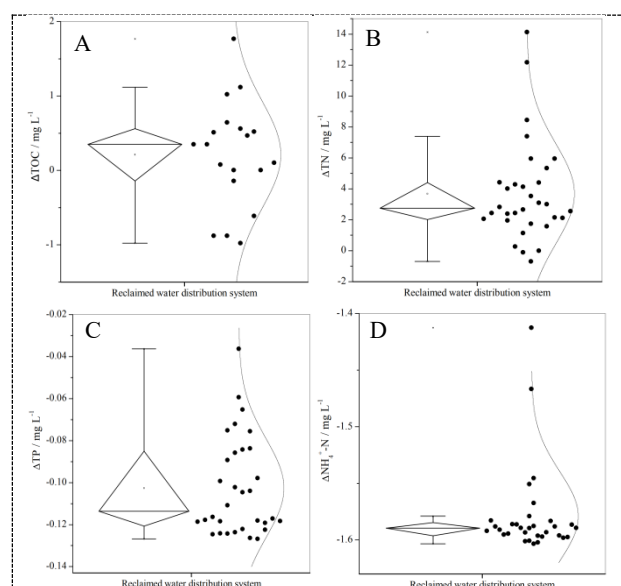


Figure 4. The box plots of difference values (i.e. ΔTOC , ΔTN , ΔTP , $\Delta\text{NH}_4^+\text{-N}$) between TOC(A), total nitrogen(B), total phosphorus(C), ammonia nitrogen(D) contents of simulated reclaimed water distribution system effluent and their respective average influent contents.

Table 2. Relative percentages of the crystal material of cement lining based on X-ray diffraction measurement.

Sample name	$\text{Ca}(\text{OH})_2$	CaCO_3	Ca_3SiO_5	Ca_2SiO_4	SiO_2	$\text{Ca}_2(\text{Al,Fe}+3)_2\text{O}_5$	Albite	Microcline
Surface layer +Inner layer0 d	15%	30%	10%	16%	10%	19%	0	0
Surface layer 180 d	0	100%	0	0	0	0	0	0
Inner layer180 d	8%	21%	8%	6%	35%	8%	7%	7%

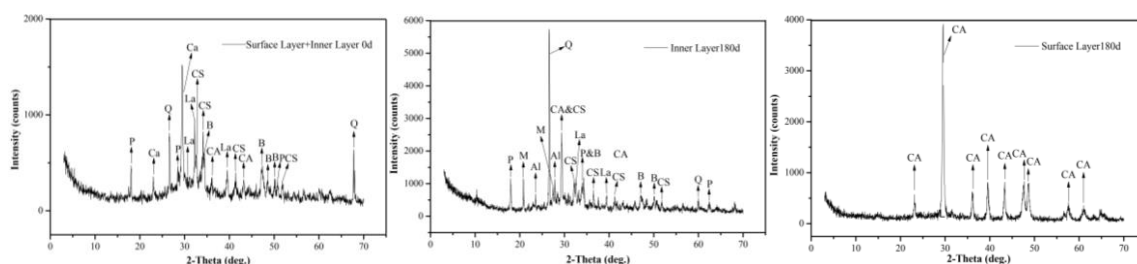


Figure 5. X-ray diffraction spectrum of the crystal material of cement lining at different test time.

4. Conclusion

The LSI, RSI, AI values of reclaimed water indicated that reclaimed water had strong corrosiveness for cement mortar lining. Also the reclaimed water with poor biological stability was easy to breed microorganism which may have microbiologically induced corrosion effect. Under the chemical and microbial corrosion of reclaimed water, the cement mortar liner surface seriously carbonized,

hydration products in liner were deteriorated, and Ca^{2+} , Si, Al and other alkaline composition were dissolved. The corrosion of cement liner may also have influence on water quality resulting in interruption of reclaimed water utilization.

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