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Effect of polyaluminium chloride water treatment sludge on effluent quality of domestic wastewater treatment

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Water resources degeneration is accelerated by the discharge of untreated wastewater and its byproducts, hence, reuse of these wastes is a major contributor to sustaining fresh water for the coming decades. In this study, the reuse of polyaluminium water treatment sludge (PA-WTS) as a flocculant aid to improve the effluent quality of wastewater during primary sedimentation is evaluated and presented. PA-WTS was collected from Gabba water treatment plant (Gabba WTP) Uganda, after the coagulation-flocculation process that makes use of aluminium chlorohydrate (ACH). The average aluminium residue concentration in PA-WTS was 3.4 mg/L. During this study, batch laboratory experiments were conducted in a jar-test apparatus in which different doses of PA-WTS were added. The results obtained showed a decrease in total suspended solids (TSS), chemical oxygen demand (COD), total ammonium nitrogen (TAN), and total phosphates (TP) in the supernatant after 30 min of settlement. The optimal PA-WTS dosage of 37.5 mL/L significantly ($P<0.05$) increased the TSS, TP and COD removal efficiencies by 15, 22 and 30%, respectively. It can be concluded that the PA-WTS positively complimented the sedimentation process in the primary treatment of wastewater to achieve better effluent quality.

Key words: Aluminium chlorohydrate, poly aluminium sludge, reuse, wastewater, water treatment sludge.

INTRODUCTION

Gabba Water Works in Kampala (Uganda) consists of three water production plants (Gabba I, Gabba II and Gabba III) and is the largest water production works in the country. It has a combined capacity to produce about 230,000 cubic meters per day. Like many other water production plants, the coagulation and flocculation process is employed for turbidity removal at Gabba water treatment plant (WTP). Recently, in a bid to improve efficiency, the Gabba WTP switched from conventional alum to aluminium chlorohydrate (ACH) which can also be referred to as poly aluminium chloride (PAC). PAC is increasingly preferred for water treatment due its lower

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Abbreviations: PA-WTS, Polyaluminium water treatment sludge; **ACH,** aluminium chlorohydrate; **TSS,** total suspended solids; **COD,** chemical oxygen demand; **TAN,** total ammonium nitrogen; **TP,** total phosphates.

alkalinity consumption as well as its lower dose requirement (Jiang and Graham, 1998). In other water treatment systems, PAC has a superior ability to inhibit phosphorus release in any anoxic conditions (Yonghong et al., 2005). The use of PAC however, still ultimately yields sludge rich in aluminium hereafter referred to as polyaluminium water treatment sludge (PA-WTS), which poses a challenge to dispose. From a chemical point of view, polyaluminum chloride (PAC) is similar to alum, except that the former contains highly charged polymeric aluminium species as well as the monomers. The solubility characteristics of PACs and alum significantly vary (Van Benschoten and Edzwald, 1990; Pernitsky and Edzwald, 2003). PACs are more soluble and have a higher pH of minimum solubility than alum which makes PAC the preferred coagulant nowadays.

When used as coagulants, both PAC and alum yield sludge containing aluminium residues, it can generally be referred to as aluminium sludge. This sludge has a gelatinous appearance, it contains aluminium with a mixture of organic and inorganic materials and hydroxide precipitates. It may also contain water treatment chemical residuals such as polyelectrolytes, powdered activated carbon, activated clay, or unreacted lime. The aluminium sludge is one of the most difficult sludges to treat because of several peculiar properties. It generally settles readily but does not dewater easily. It consists mainly of flocs with water content varying between 95 and 99%, which are the typical levels found in waterworks sludge before and after thickening (Twort et al., 2000). Due to the difficulty in dewatering of the aluminium sludge, in the past the sludge was discharged into water sources, like rivers or lakes. However, nowadays the final disposal of the coagulation sludge occurs by land filling with little prospect of reuse (Hsu and Hseu, 2011).

Literature estimates the worldwide aluminium water treatment sludge to be 10,000 t/day (Dharmappa et al., 1997). These volumes will only keep increasing as long as aluminium compounds/complexes remain to be the major coagulant in water purification processes. Therefore, sustainable management of such sludge continues to become an increasing concern in the water industry. The beneficial reuse of aluminium sludge is highly desirable and has continued to attract considerable research efforts. A number of researchers have already indicated that alum sludge can be a value-added raw material for beneficial reuse. Ferreira and Olhero (2002) proposed a treatment method towards recycling of aluminium rich sludge to produce high alumina refractory ceramics. Hsu and Hseu (2011) and Ulen et al. (2012) demonstrated that aluminium sludge can be used to reduce phosphorus availability and mobility during soil amendment. Other sets of studies for example (Yang et al., 2006b; Yang, 2011) have successfully increased removal efficiency of especially phosphorus from constructed wetlands, when the dried aluminium sludge cake was used there. Also, different studies by Chao (2011) and Zhao et al. (2008) showed considerable phosphorus removal from stabilisation ponds and reed bed treatment systems, respectively when aluminium water treatment sludge was reused. When aluminium hydroxide sludge was discharged to a sewer in a treatment plant, phosphate removal was up to 94% (Horth et al., 1994). Similarly, Guan et al. (2005) observed that both suspended solids (SS) and COD removal efficiencies were improved by 20 and 15%, respectively when Al-WTS was reused in primary sewage treatment.

A number of studies have already given insight into reuse of alum sludge, but many water treatment plants are now adopting PAC whose sludge characteristics differ from alum sludge. It is therefore necessary to study the possibility of reuse of sludge derived from water treatment where PAC is used. It is against this background that this study sought to explore the reuse of PA-WTS in order to improve wastewater effluent from the primary treatment stage. Low rate mixing was used to minimize energy input while at the same time enhancing flocculation. The effect of different doses of PA-WTS from Gabba water treatment plant (Kampala) on the primary treatment of wastewater was monitored.

MATERIALS AND METHODS

Sample collection

PA-WTS was collected at three instances from Gabba II water treatment plant, in February and March 2012. Gabba Water Works in Kampala is the largest water production plant complex in Uganda. It consists of three water production plants, Gabba I, Gabba II and Gabba III whose individual capacities are 70,000, 80,000 and 80,000 m^3/day, respectively. Water treatment at Gabba WTP II is done in the order of screening, pre-chlorination, clarification, coagulation, flocculation, sedimentation, rapid gravity filtration, post chlorination and finally pH correction. The plant uses ACH ($Al_2(OH)_2Cl$) during flocculation, whose ions remain as a residue in the sludge. Domestic wastewater was collected at the inlet of Bugolobi sewage treatment plant (STP) in Kampala, Uganda. The STP is the largest sewage treatment plant in Uganda. It employs physical and biological treatment by use of screens, detritus basin, primary, settling tanks, trickling filters and clarifiers in that order.

Experimental set up

The characteristics of Gabba II PA-WTS as well as the domestic wastewater were determined at the beginning of each experimental run. Bench tests were run in which different volumes of PA-WTS were added per liter of sewage (0, 12, 25, 37.5, 50, 62.5, 75, 87.5, 100, 112.5, 125, 137.5 and 150 mL of PA-WTS per liter wastewater). These doses had a corresponding aluminum concentration of 0, 0.03, 0.07, 0.10, 0.14, 0.17, 0.20, 0.24, 0.27, 0.31, 0.34, 0.37, 0.41 mg Al/L wastewater, respectively.

Selection of the mixing time

To determine the suitable mixing time, the experiments were done

Table 1. Average ± SD of selected parameters of the PA-WTS and raw waster from Bugolobi STP used in this study.

Parameter	PA-WTS	Raw wastewater
TSS (mg/L)	1084± 41	563 ± 179
COD (mg/L)	2260 ±176	1197 ± 248
TAN (mg/L)	11 ± 2	35 ± 13
TP (mg/L)	14 ± 3	15 ± 5
pH	7.2 ± 0.4	7.9 ± 0.3
Residual aluminum (mg/L)	3.4 ± 0.3	ND

at varying times of 0, 5, 10 and 20 min. A mixing rate of 25 rpm was used to minimize high energy costs considering its application in the developing world. Upon mixing for the given times and rate indicated above, the mixtures were left to settle for 30 min. After the settling period, samples from the supernatant were taken and TP, COD, TAN and TSS were analyzed with HACH DR 5000 Spectrometer using the standard methods (APHA, 2005). The pH was measured with a Toledo pH meter. The same parameters were determined for the wastewater prior to any treatment.

Selection of optimal dose and data analysis

The suitable mixing time selected from the procedures above was used for further experiments of determining the optimal PA-WTS dose. Bench tests for each dose were done in triplicates at this mixing time and rate, and the same parameters were measured. Removal efficiencies of the analyzed parameters at different doses of PA-WTS were then compared to get the optimal sludge dose. The dose corresponding to the maximum gradient of the removal efficiency curve was selected as the optimal dose. The optimum dose and control experiments were repeated 10 times to ensure reliability of the results. An F test was used to test for homogeneity, after which a T–tests was used to verify the significant difference between parameters measured at the two doses**.**

RESULTS AND DISCUSSION

PA-WTS and untreated sewage characteristics

The characteristics of the Gabba II PA-WTS and raw waster from Bugolobi STP are shown in Table 1. The results show that the average residual aluminum in the PA-WTS was 3.4 mg/L. These are much lower doses than what has been used in other studies using alum, for example it was 313 mg Al/L alum sludge for Horth et al. (1994). One of the the advantages of using pre-polymerised inorganic coagulants over alum, is their lower dose requirement (Jiang and Graham, 1998). This typically yields low aluminium concentration for sludge originating from ACH coagulants in comparison to that originating from alum.

The results of the Bugolobi STP wastewater show that it is of very high strength (Metcalf and Eddy, 1991). The maximum values TSS, TP, TAN and COD of eight samples of BSTP wastewater sampled at different times were 876, 20, 51 and 1442 mg/l, respectively. The wastewater characteristics are known to vary depending on the conditions which are typical of our results.

Selection of mixing time

Generally, the concentration of all other parameters with the exception of TP and TSS did not differ at various mixing times (Figures 1A to D) for a mixing rate of 25 rpm. This implies that mixing time is not important for removal of TAN and COD. On the other hand, generally TP in the supernatant at all mixing times of 0, 5, 10 and 20 min decreased with increased dose of PA-WTS but decreased more at 20 and 10 min (Figure 1C). The concentration of TSS in the supernatant at different doses and mixing times are shown in Figure 1D. Generally, TSS concentration in the supernatant at all mixing times of 0, 5, 10 and 20 min decreased with increased dose of PA-WTS. The final concentration of TSS at zero mixing was constantly higher than that at 5, 10 and 20 min for all the doses of PA-WTS. Mixing increases contact between PA-WTS flocs and suspended matter, hence more decrease of TSS is observed in the supernatant of the mixed samples. The mechanisms for removal are discussed at a later stage in this study. The mixing time of 5 min was selected as the suitable mixing time since it was the smallest time that could achieve more TSS decrease.

Selection of optimal dose

To select the optimal dose, the removal efficiency of different parameters at varying PA-WTS doses was compared. The pH (data not shown) was observed to be constant with increase in the PA-WTS dose throughout the study. A pH of 8.0 was maintained in one of the sets, of experiment, while the other sets maintained a pH of 7.8. The pH has been found to affect coagulation and flocculation. Optimum pH values for re-use of alum sludge were proposed to be between 6 and 10 for simultaneous removal of TSS, turbidity, and anionic surfactants. On the other hand, the optimal pH for the removal of total COD was between 8 and 12 (Siriprapah et al., 2011). The pH between 7-8 maintained in our

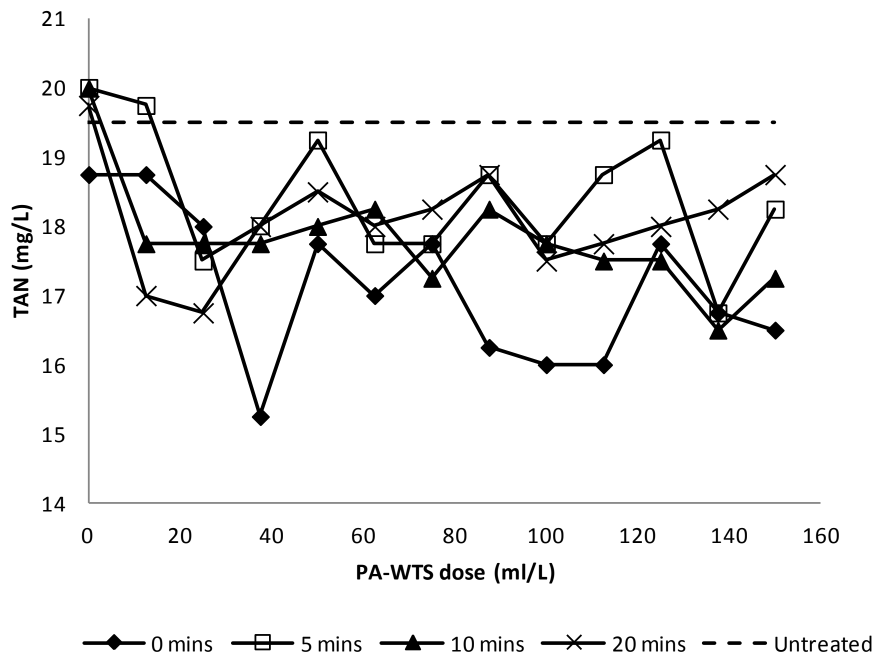

Figure 1A. TAN values for wastewater supernatant after adding different PA-WTS doses at different mixing times and settlement time of 30 min.

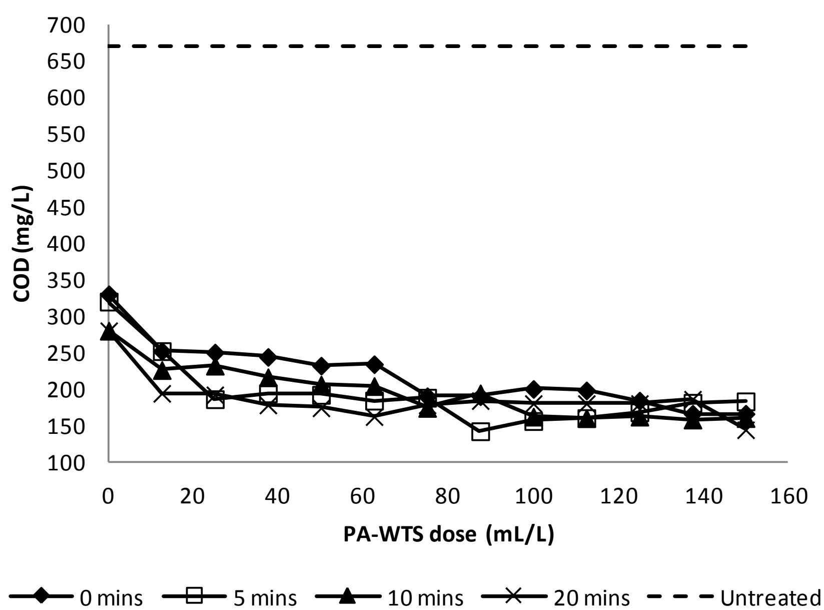

Figure 1B. COD values for wastewater supernatant after adding different PA-WTS doses at different mixing times and settlement time of 30 min.

experiment can be said to be within an optimal range for TSS and COD removal.

All other measured parameters generally decreased with increased PA-WTS dose (Figure 2). The average removal efficiency of TSS in the supernatant kept increasing with increase in PA-WTS dose. The influence of the PA-WTS dose on the COD in the wastewater is also shown (Figure 2). The mean COD removal efficiency in the supernatant generally increased with initial increase in PA-WTS doses. This is in agreement with other studies which showed that TSS and COD can be removed by use of alum sludge (Guan et al., 2005;

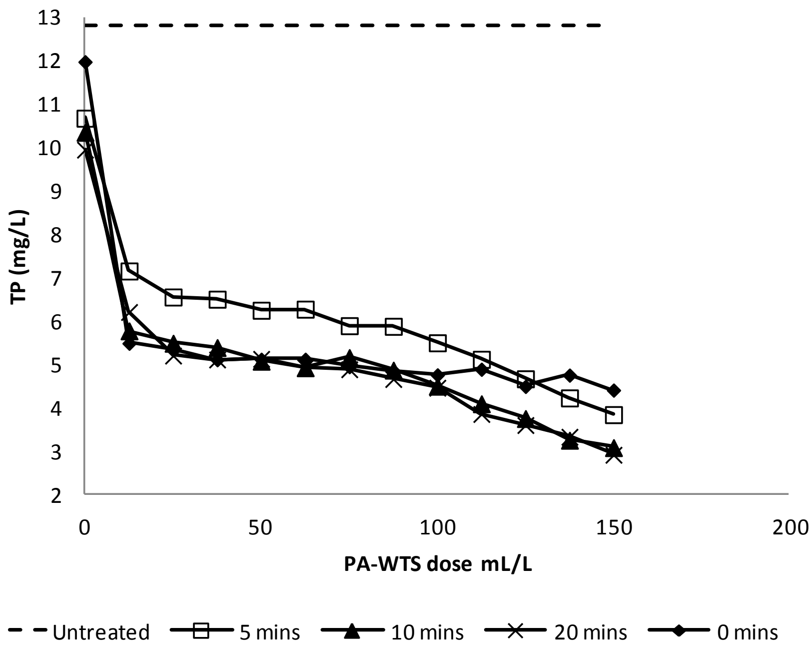

Figure 1C. TP values for wastewater supernatant after adding different PA-WTS doses at different mixing times and settlement time of 30 min.

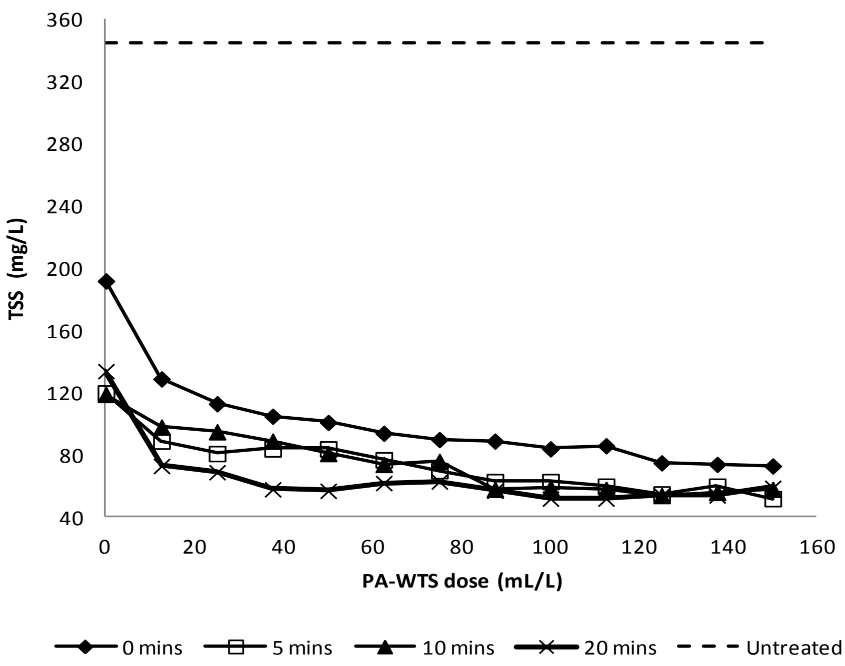

Figure 1D. TSS values for wastewater supernatant after adding different PA-WTS doses at different mixing times and settlement time of 30 min.

Yang et al., 2011). However, our study shows a slight COD decrease after a PA-WTS dose of 90 mL/L. The average TP removal efficiency increased slightly with the least PA-WTS dose and kept increasing slightly with further increase in the PA-WTS dose (Figure 2). Similar trends are shown for TAN. As illustrated in Figure 2, the maximum gradient removal was observed to occur at PA-WTS doses beween 0 and 12.5 mL for TSS, 0

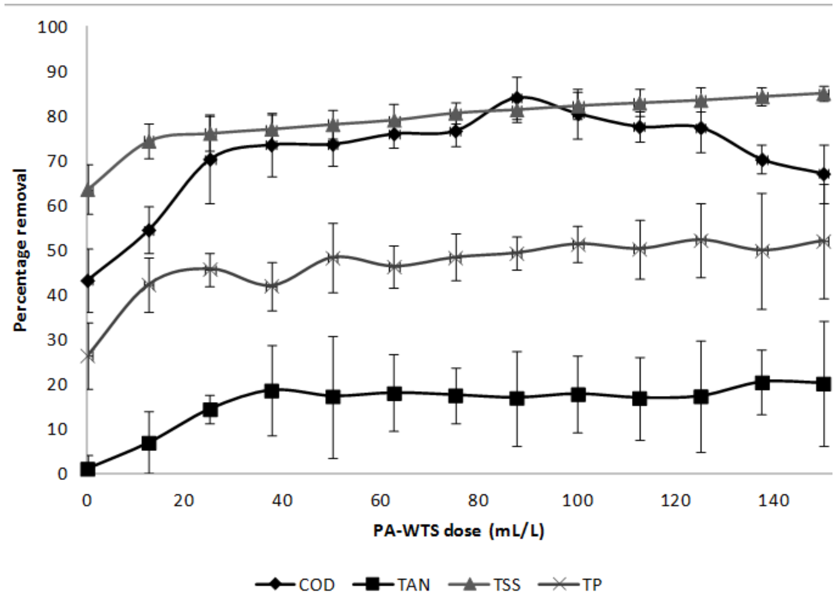

Figure 2. Effect of different doses of the PA-WTS on COD, TSS, TAN and TP removal efficiency from wastewater.

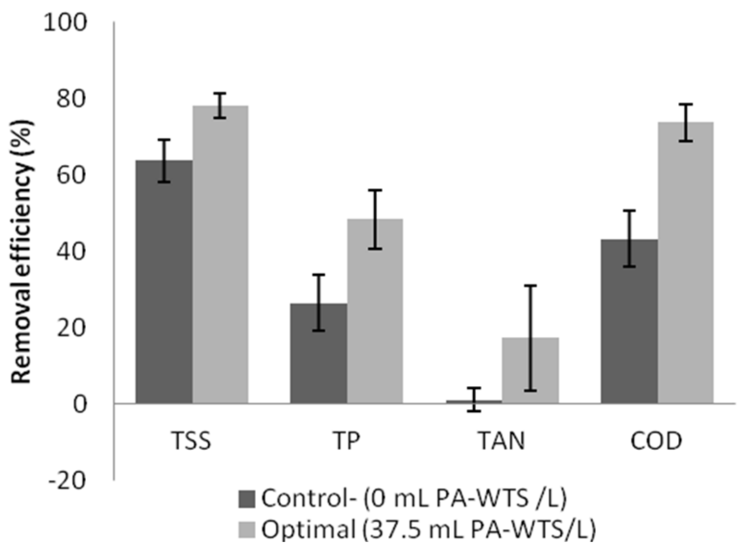

Figure 3. Average percentage removals ± SD of COD, TSS, TAN and TP for the control and the optimal dose at 5 min mixing time and settlement of 30 min.

and 37.5 mL for TP, 0 and 37.5 mL for TAN and between 0 and 25 mL for COD. The dose of 37.5 mL PA-WTS /L was hence chosen as the optimal dose in order to cater for all doses which showed maximum gradient removal.

Comparison at optimal dose

Experiments were repeated with the optimal PA-WTS dose (37.5 mL PA-WTS /L) in comparison to the control (0 mL PA-WTS /L). The average percentage removal efficiencies of TSS, TP, TAN and COD in the supernatant at both doses were compared and are shown in Figure 3. After testing for homogeneity a T test was used to verify the significant difference between parameters measured at the two doses**.** The tests showed homogeneity for all parameters except TAN and further revealed significant difference between the measured parameters at the two doses except for TAN. It was found that the optimal PA-WTS dosage of 37.5 mL/L (0.14 mg Al/L) significantly ($P<0.05$) increased the removal efficiency of TSS from

64±6, to 78±3, TP from 26±7 to 48±8 and COD from 43±7 to 74± 5 (Figure 3). TAN removal efficiency was however not significantly different for the two doses, but the trend was that it increased from 1±3 to 19±13 (Figure 3).

On average the removal efficiencies of TSS, TP, TAN and COD were increased by 15, 22, 18 and 30%, respectively at the optimal dose of 37.5 mL/L (0.14 mg Al/L). These are higher removals per aluminium concentration when compared to the removal increments observed by Guan et al. (2005). The latter authors observed an increment of 20 and 15% for SS and COD, respectively at a sludge dose of 18 to 20 mg Al/L when alum sludge was used. This may arise due to the difference in properties of the two sludges which enhance different removal mechanisms during flocculation. The four distinct mechanisms of coagulation and flocculation include double layer compression, adsorption and charge neutralization, sweep coagulation and inter particle bridging/complexion (Amirtharajah and O'Melia, 1991). Alum sludge usually yields flocs with a negative charge, which is similar to the charge in wastewater. Particulate pollutant removal efficiency in the alum sludge is therefore predominantly as a result of the sweep mechanism and not necessarily neutralisation (Guan et al., 2005). In contrast, the flocs formed with the high basicity non-sulfated PAC, which is typical of the sludge used in this experiment, exhibit a higher positive charge at a pH of above 7 (Pernitsky and Edzwald, 2003). This positive charge is likely to enhance neutralisation which would contribute to more particulate removal when PA-WTS is used. The neutralisation contribution may however still be small compared to the sweep mechanism since as discussed already, the residual aluminium in PA-WTS is small compared to that in the alum sludge. Another fact that could lead to higher removal when PA-WTS was used can be explained by the observations of Gregory and Dupont (2001). On comparing alum and PAC coagulants, they observed that PAC products form larger and stronger flocs than alum. It can be anticipated that larger flocs will provide more space for particulate matter adsorption and attachment than the smaller flocs. The PA-WTS used in this study can therefore be said to have sufficient floc sizes on which particulate matter attach when gently stirred and hence settle out faster than for samples without PA-WTS. Hence the supernatant TSS and COD in this study kept decreasing with increase in the sludge dose because higher doses of PA-WTS had more flocs. These could sweep out more particulate matter from the wastewater.

Evidence from literature shows that aluminium sludge can help remove phosphorus in wastewater (Horth et al., 1994; Yang et al., 2006b; Yang et al., 2011). The removal is accredited to adsorption and chemical precipitation enhanced by the abundant presence of aluminium ions in the sludge (Kim et al., 2003). In addition, Yang et al. 2006b) showed that the adsorption capacity can be affected by pH and the different ions present. They observed a remarkable decrease in phosphorous (P) adsorption capacity of the aluminium sludge when the pH was increased from 4.3 to 9. Compared to the mentioned studies, it is clear that the P adsorption capacity of the aluminum sludge in this study was negatively impacted by low aluminum ions in the PA-WTS combined with the pH of 7.8 and 8 that was imposed. The removal efficiency of TP was 45% (Figure 3) with the optimal Al dose of 0.14 mg Al/L compared to other studies which achieved more than 90% phosphorus removal. Horth et al. (1994) observed phosphate removal up to 94%, at an alum sludge dose of 94 mg Al/L. Similarly, soluble phosphorus removal from a stabilisation pond increased to >90% with a dose of sludge of 131 mg/L (Yang et al., 2011).

Conclusions

PA-WTS was added to wastewater as a flocculant aid with an objective to determine if it will improve effluent quality during sedimentation. There was an increased removal of TSS, TP, TAN and COD in the Bugolobi STP wastewater supernatant after mixing it for 5 min at a rate of 25 rpm and allowing it to settle for 30 min. The wastewater was prior dosed with PA-WTS doses of 0, 12, 25, 37.5, 50, 62.5, 75, 87.5, 100, 112.5, 125, 137.5 and 150 mL PA-WTS/L. The study showed that an optimal dose of 37.5 mL PA-WTS /L significantly increased the removal efficiency of TSS, COD and TP from water during sedimentation. TSS, TP and COD removal efficiencies were significantly increased by 15, 22 and 30%, respectively. Based on this study, it can be concluded that incorporating PA-WTS dosing before the primary settling unit is a promising venture towards better effluent quality in wastewater treatment systems. For the existing plants, modifications done to allow mixing of PA-WTS before primary settling, would go a long way in improving effluent quality of the settling tank. While for the new plants, the design size of the settling tank can be decreased since a shorter retention time is needed with PA-WTS. This will require lower capital costs for new plants, in addition to the better effluent.

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