Co-Conditioning of the Anaerobic Digested Sludge of a Municipal Wastewater Treatment Plant with Alum Sludge: Benefit of Phosphorus Reduction in Reject Water

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ABSTRACT: In this study, alum sludge was introduced to co-conditioning and dewatering with an anaerobic digested sludge from a municipal wastewater treatment plant, to examine the role of the alum sludge in improving the dewaterability of the mixed sludge and also in immobilizing phosphorus in the reject water. Experiments have demonstrated that the optimal mix ratio for the two sludges is 2:1 (anaerobic digested sludge:alum sludge; volume basis), and this can bring approximately 99% phosphorus reduction in the reject water through the adsorption of phosphorus by alum in the sludge. The phosphorus loading in wastewater treatment plants is itself derived from the recycling of reject water during the wastewater treatment process. Consequently, this co-conditioning and dewatering strategy can achieve a significant reduction in phosphorus loading in wastewater treatment plants. In addition, the use of the alum sludge has been shown to beneficially enhance the dewaterability of the resultant mixed sludge, by decreasing both the specific resistance to filtration and the capillary suction time. This is attributed to the alum sludge acting in charge neutralization and/or as adsorbent for phosphate in the aqueous phase of the sludge. Experiments have also demonstrated that the optimal polymer (Superfloc C2260, Cytec, Botlek, Netherlands) dose for the anaerobic digested sludge was 120 mg/L, while the optimal dose for the mixed sludge (mix ratio 2:1) was 15 mg/L, highlighting a huge savings in polymer addition. Therefore, from the technical perspective, the co-conditioning and dewatering strategy can be viewed as a “win-win” situation. However, for its full-scale application, integrated cost-effective analysis of process capabilities, sludge transport, increased cake disposal, additional administration, polymer saving, and so on, should be factored in. Water Environ. Res., 79, 2468 (2007).

KEYWORDS: adsorption, alum sludge, biological phosphorus removal, conditioning, anaerobic digested sludge, phosphorus removal, nutrient control.

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Introduction

As phosphorus is a limiting-growth nutrient for algae in most receiving water bodies, it should be removed before any discharge, to reduce the dangers of eutrophication. The biological phosphorus removal (BPR) process has been widely used in phosphorus removal from municipal and industrial wastewater because of its lower costs and reliability for wastewater treatment (Horan, 1990; Tchobanoglous et al., 2003). In the BPR process, phosphorus in the influent is incorporated to the cells of microorganisms. This can be achieved in two ways—(1) microbial growth of the phosphate-accumulating organisms (PAOs) and/or normal microorganisms, and (2) the “luxury uptake” of phosphate by PAOs (Comeau et al., 1986; Sedlak, 1995). Consequently, phosphate is removed from the BPR process with the excess activated sludge, which may contain phosphorus in the range 3 to 6% (Sedlak, 1995) on a dry-weight basis, or 8 to 12.3% on a volatile-suspended-solids basis (Liu, 1995; Liu et al., 2000). In municipal wastewater treatment plants (WWTP), the phosphorus-enriched excess sludge and the primary sludge are typically thickened to reduce the sludge’s volume and then mixed together before being fed to the anaerobic digester for stabilization. However, phosphorus can be released when bacteria that contain stored phosphorus (i.e., PAOs) are subjected to anaerobic conditions, which include thickening and/or anaerobic digestion, leading to a phosphorus-enriched supernatant (generated from the thickening process) and phosphorus-enriched filtrate obtained from mechanical dewatering of the sludge (Jardin and Popel, 1994).

Both the phosphorus-enriched supernatant and the filtrate are termed as reject water in the paper thereafter. The reject water must be recycled back to the main wastewater stream for treatment because the quality of the reject water is typically far below the discharge standard of municipal WWTPs (Janus and Roest, 1997). Popel and Jardin (1993) reported a theoretical estimation that the supernatant from the thickening process could potentially result in 5% phosphorus feedback through reject water recycling. More significantly, under a normal operating condition of a BPR process, the phosphate release can theoretically result in 20 to 43% phosphorus feedback, and the possible phosphorus feedback can reach up to 95% of the original phosphorus loading at a WWTP (Popel and Jardin, 1993). Consequently, if the readily biodegradable chemical oxygen carbon (rbCOD) for biological phosphorus removal is not sufficient, the return of the reject water with a high level of phosphorus can lead to reduced phosphorus removal efficiency of the BPR process (Tchobanoglous et al., 2003).

To remove phosphorus from the recycled reject water, several attempts, including chemical addition, to reduce phosphorus level have been made. Generally, lime, aluminium, iron, and magnesium salts can be used in similar ways as in standard chemical phosphorus precipitation (Jenkins et al., 1971). However, this can lead to
increased operational cost and/or sludge production, which may not favor its use. For this reason, other cost-effective treatment methods and materials are being investigated. Industrial byproducts, particularly those that contain high levels of alum and/or iron, have been considered a cost-effective alternative to metal salts to remove phosphorus from wastewater (Huang and Chiswell, 2000; Kim et al., 2002; Roques et al., 1991). Recent studies have also focused on the reuse of aluminum-based drinking water treatment sludge for phosphorus removal, because it is an inescapable byproduct during drinking water production and has exhibited a strong affinity for phosphorus (Makris et al., 2005; Razali et al., 2007; Yang, Tomlinson, Kennedy, and Zhao, 2006).

One of the alternative uses of alum sludge is in the co-conditioning and dewatering with the anaerobic digested sludge. It is expected that alum sludge will be a potential adsorbent for phosphorus removal from the reject water. Furthermore, co-conditioning of the two kinds of sludges may reduce the polymer dose required to achieve good dewaterability, because the alum sludge may act as a skeleton builder in the mixed sludge and thus has a beneficial effect in the dewatering process (Lai and Liu, 2004). In this study, an attempt was made to co-condition and dewater anaerobic digested sludge (generated from a municipal WWTP) with alum sludge (produced from a drinking water treatment works) for the purpose of exploring the following:

1. Dewaterability of the mixed sludge under different mix ratios,
2. Influence of alum sludge addition on polymer dose during conditioning, and
3. Phosphorus reduction in reject water after dewatering.

Moreover, possible application of the results from this study to a municipal WWTP in Dublin, Ireland, is discussed.

Materials and Methods

Digested Activated Sludge and Alum Sludge. The anaerobic digested sludge was collected from the anaerobic digestion unit of a municipal WWTP located in northeast Dublin. The WWTP uses an anaerobic/anoxic/aerobic (A²O) process for municipal wastewater treatment. The primary sludge (from the primary sedimentation tank) and the excess activated sludge (from the secondary sedimentation tank) were both thickened and thereafter mixed together before being fed to the anaerobic digestion unit. The anaerobic digested sludge contained 97.89% water and approximately 603.0 mg phosphorus/L of phosphorus in its supernatant. To examine the phosphorus in the solids phase of the sludge, a laboratory-model centrifuge (MSE Super Minor, Sussex, United Kingdom) operated at 3000 r/min was used to separate the solids. The solids were then washed with distilled water, until the residual phosphate in the wash water was less than 0.05 mg phosphorus/L. Thereafter, the solid was dried at 103 ± 2°C. The weighed solid was digested using the standard method of nitric acid digestion (3030 E; APHA et al., 1992). The phosphate concentration in the solution of the nitric acid digestion was measured.

The sludge, with a moisture content of 95.21%, was collected from the holding tank of the sludge dewatering unit of a water treatment works in southwest Dublin, where aluminium sulfate is used as a coagulant, and a cationic polymer (FO-4140 PWG) is used as a coagulation aid treating a nearby reservoir water. Characterization of the alum sludge was done by examining its physical and chemical properties. To examine the chemical components, the alum sludge was subjected to a 103 ± 2°C heating process. The solids obtained were then digested and analyzed using an inductively coupled plasma-atomic emission spectrometer (ICP-AES, IRIS Advantage, Thermo Elemental, Franklin, Massachusetts), ion chromatography (DX-120, Dionex, Sunnyvale, California), and total organic carbon (TOC)-VCSH (Shimadzu, Tokyo, Japan).

The sludges used in this study were taken regularly, every 2 weeks, from the WWTP and the water treatment works. Characterization of the sludges during the 2-week period showed insignificant change according to the measurements of their dewaterability and chemical components, although the collected sludges showed some scatter regarding their properties.

Co-Conditioning Procedure. Sludge conditioning tests were conducted using the anaerobic digested sludge and the mixed sludge (the mixed sludge refers to the mixture of the anaerobic digested sludge and alum sludge at a mix ratio of 2:1, v/v, anaerobic digested sludge: alum sludge). The 2:1 mix ratio was determined as the optimal mix ratio that ensures the lowest phosphate concentration in the supernatant with the least amount of alum sludge addition. A cationic polyelectrolyte named Superfloc C2260 (Cytec, Botlek, Netherlands), which is a high-molecular-weight-polymer with a charge density of 40%, was used as a chemical conditioner. The conditioning tests were performed using a jar-stirring device, where the sludge was mixed with the various polymer doses at a mean velocity gradient (G) value of 500 seconds⁻¹ for 20 seconds, followed by a reaction process which was at a G value of 34 seconds⁻¹ for 294 seconds. This provides a GT value of 10 000, which is considered as the most critical determinant factor to ensure the shear conditions, particularly for similar shear conditions, such as in the belt press dewatering process (Novak and Lynch, 1990; Novak et al., 1993).

The dewaterability of the sludge was evaluated using the capillary suction time (CST) and specific resistance to filtration (SRF). The CST was determined using a Triton CST Apparatus (Triton WPRL, Type 130, Dunmow Essex, United Kingdom) with a CST paper of size 7 cm × 9. The SRF tests were performed using a standard Buchner funnel with a Whatman No. 1 qualitative filter paper (70-mm diameter). A 50-kPa vacuum suction was applied. The images of the sludge appearance under polymer conditioning were captured using an image acquisition system, which consists of a Dell Workstation 400 (Dell, Round Rock, Texas) equipped with an IC-RGB (image capture [IC] for red, green, and blue [RGB]) frame grabber (Imaging Technology Inc., Bedford, Massachusetts) and a charge-coupled device camera (XC-003P, Sony, Tokyo, Japan).

Phosphorus Adsorption by Alum Sludge. To determine the phosphorus adsorption capacity of the alum sludge, a series of batch stirring tests was conducted by adding a predetermined amount of the liquid alum sludge to an artificial phosphate solution. The artificial phosphate solution was prepared by dissolving preweighed potassium dihydrogen phosphate (KH₂PO₄) to distilled water. The mixture was then adjusted to pH values of 6.5, 7.0, and 7.5, using either sulfuric acid (0.01 M) or sodium hydroxide (0.1 M), to simulate the real pH range when digested sludge and alum sludge were mixed. The mixture was then mechanically agitated to facilitate adsorption over a 6-hour predetermined equilibrium time. After adsorption, equilibrated samples were filtered using 0.45-μm millipore filter paper (Millipore, Billerica, Massachusetts) and analyzed for phosphate concentration. Phosphate concentrations and pH values were determined using the stannous chloride method (4500-P D; APHA et al., 1992) and a pH meter (pH 325; Wissenschaftlich-Technische-Werkstätten, Weilheim, Germany), respectively.
Equilibrium data were fitted with the Freundlich model in the following form (Tchobanoglous et al., 2003):

\[ \lg \left( \frac{x}{m} \right) = \lg K_f + \frac{1}{n} \lg C_e \]  

Where

- \( x/m \) = mass of adsorbate adsorbed per unit mass of adsorbent (mg phosphorus/g sludge),
- \( K_f \) = Freundlich capacity factor (mg phosphorus/g sludge) \( \cdot \) (L water/mg phosphorus)\(^{1/n}\),
- \( C_e \) = equilibrium concentration of adsorbate in solution after adsorption (mg phosphorus/L), and
- \( 1/n \) = Freundlich intensity parameter.

By plotting \( \lg(x/m) \) versus \( \lg C_e \), the constants in the Freundlich isotherm can be obtained. All the experiments were repeated twice, and the average value of measurements was reported.

**Results**

**Characteristics of the Sludges—Anaerobic Digested Sludge.**

Figure 1 shows that the water content of the anaerobic digested sludge ranged from 96.95 to 98.21%, with an average of 97.89%. The phosphate in the anaerobic digested sludge is distributed into two phases—the aqueous phase (representing the phosphate in the supernatant) and the solid phase (representing the phosphate in the sludge solid). Approximately 78% of phosphate is distributed within the aqueous phase, while 22% of the phosphate is distributed within the solid phase. Thus, it is believed that phosphate in the reject water is derived predominantly from the supernatant of the anaerobic digested sludge. Therefore, to reduce the phosphate level during the recycling of the reject water to the wastewater treatment process, the focus should be placed on the phosphate in the aqueous phase of the anaerobic digested sludge.

The CST and SRF of the anaerobic digested sludge are illustrated in Figure 2. From the samples tested, the CST ranged from 463.3 to 473.6 seconds, while the SRF ranged from \( 40.01 \times 10^{13} \) to \( 65.43 \times 10^{13} \) m/kg. Although all the sludge samples were from the same source, their CST and SRF values showed some variation. This could be attributed to the operating conditions, including sludge transfer and storage methods of the WWTP (Nissen and Vesilind, 1974). From Figure 2, the dewaterability of the sludge can be characterized as poor.

**Characteristics of the Sludges—Alum Sludge.**

The physical and chemical properties of the alum sludge are shown in Table 1. The water content of the sludge was 95.21%. The alum sludge contained 194.5 mg aluminum/g sludge (dried at 103 ± 2°C) or 0.93% aluminum in 1 g of liquid alum sludge. Compared with other metal ions, such as magnesium, calcium, and iron, the aluminum ion can be considered as the dominating metal ion. The other principal chemical component is natural organic matter, such as

| Properties                  | Unit        | Average | ±standard deviation, \( n = 3 \) |
|-----------------------------|-------------|---------|----------------------------------|
| pH                          | —           | 6.14    | 0.01                             |
| Water content % (at 103 ± 2°C) | %          | 95.21   | 0.09                             |
| Aluminum mg-Al/g-sludge     | mg-Al/g-sludge | 194.49  | 0.51                             |
| Iron mg-Fe/g-sludge         | mg-Fe/g-sludge | 5.20    | 0.13                             |
| Calcium mg-Ca/g-sludge      | mg-Ca/g-sludge | 5.18    | 0.18                             |
| Magnesium mg-Mg/g-sludge    | mg-Mg/g-sludge | 1.59    | 0.05                             |
| Humic acid (as TOC) mg-C/g-sludge | mg-C/g-sludge | 118.44  | 3.47                             |
| CI⁻ mg-CI/g-sludge          | mg-CI/g-sludge | 11.39   | 0.74                             |
| SO₄²⁻ mg-SO₄²⁻/g-sludge     | mg-SO₄²⁻/g-sludge | 8.86    | 0.49                             |
| Silicon mg-Si/g-sludge      | mg-Si/g-sludge | 6.79    | 0.48                             |

Figure 1—Water content and phosphate (P) distribution in different samples of the anaerobic digested sludge.

Figure 2—SRF and CST of the anaerobic digested sludge.

Figure 3—SRF and CST of the alum sludge.

Table 1—The physical and chemical properties the alum sludge.
humic acid, expressed as total organic carbon (TOC), which is 118.4 mg carbon/g sludge (dried at 103 °C).

Figure 3 illustrates the values of CST and SRF of the alum sludge. The CST ranged from 169.8 to 197.2 seconds, while the SRF ranged from $1.99\times10^{13}$ to $4.14\times10^{13}$ m/kg. Compared with the results presented in Figure 2, it becomes clear that the alum sludge exhibited better dewaterability than the anaerobic digested sludge.

Figure 4 shows the adsorption isotherms of phosphate adsorbed onto the alum sludge at different pH conditions. The adsorption capacity factor ($K_f$) was calculated using the Freundlich isotherm model (see eq 1). The value of $K_f$ increased from 5.38 to 33.4 L/g alum sludge when the pH was decreased from 7.5 to 6.5. This indicates that the adsorption behavior is pH-dependent, with the adsorption favored at a low pH value.

**Optimal Mix Ratio of the Sludges.** To examine the effect of the amount of alum sludge addition on both the digested sludge dewaterability and the phosphorus level in the supernatant, different ratios (v/v, digested sludge:alum sludge) of the two sludges were mixed, and the resultant sludge dewatering characteristics and the supernatant phosphorus concentration of the mixed sludge were measured. The results are shown in Figures 5 and 6.

It can be seen, from Figure 5, that the addition of alum sludge can improve the dewaterability of the anaerobic digested sludge. Improved dewaterability can be obtained with an increasing amount of alum sludge addition. The SRF of the anaerobic sludge was decreased from $48.3\times10^{13}$ to $13.4\times10^{13}$ m/kg, and the corresponding CST was reduced from 451.1 to 318.9 seconds, while the mix ratio was changed from 1:0 to 1:1 (see Figure 5). Figure 6 shows the phosphorus concentration, in both the supernatant of the anaerobic digested sludge and that of the mixed sludge, at different mix ratios. It can be clearly seen that the addition of alum sludge can lead to a significant reduction of phosphorus in the aqueous phase of the mixed sludge. The initial phosphorus concentration in the anaerobic digested sludge ranged from 597.3 to 674.5 mg phosphorus/L.

However, the range of phosphorus concentration in the supernatant was 208.0 to 251.1, 55.2 to 64.3, 0.14 to 3.20, and 0.17 to 0.65 mg phosphorus/L at mix ratios of 3:1, 2.5:1, 2:1, and 1:1, respectively (see Figure 6). By considering the fact that the addition of alum sludge can potentially increase the overall volume of the mixed sludge, which will increase the hydraulic load on the dewatering unit in the WWTP, the optimal mix ratio was chosen as 2:1 for the ensuing sludge conditioning tests using organic polymer as a conditioner.

**Polymer Conditioning of the Mixed Sludge.** Figure 7 shows the dewatering behavior of the mixed sludge (at ratio of 2:1) conditioned by a cationic polyacrylamide Superfloc C2260. The phosphorus concentration in the supernatant of the mixed sludge during the conditioning process is also jointly illustrated in the figure. The results show that the polymer conditioning results in a significant improvement of the mixed sludge dewaterability, as evaluated by the SRF and CST. The values of SRF and CST decreased from 30.01 to 2.74 $\times 10^{13}$ m/kg and from 421 to 33.9 seconds, respectively, while the polymer dose was increased from 0 to 15 mg/L. The optimal polymer dose for the mixed sludge was determined to be 15 mg/L, because a further increase of polymer dose beyond that value did not bring about any further decrease of SRF or CST, as shown in Figure 7.

In addition, Figure 7 shows that the phosphate concentration in the supernatant was very low at all the different polymer doses, ranging from 0.15 to 3.1 mg phosphorus/L.
Figure 8 shows images of the mixed sludge (mix ratio 2:1) at various doses of Superfloc C2260 during conditioning. Although the captured images represent the qualitative description of the sludge at the specific conditions in this study, the change of sludge appearance, in terms of particle aggregation/floc and free water released, with increased polymer dose, can be clearly seen.

As a comparison, Figure 9 provides evidence to illustrate the changes of SRF and CST with various doses of polymer (Superfloc C2260) for the digested sludge only. The values of SRF decreased from $4.65 \times 10^{13}$ to $3.21 \times 10^{13}$ m/kg, and CST decreased from 484.4 to 25.3 seconds, with increasing polymer dose to 120 mg/L. However, it is interesting to note that a large amount of polymer was added, and the optimal dose was 120 mg/L, which corresponds to the lowest SRF and CST values, as illustrated in Figure 9. Increasing the polymer dose beyond the optimal dose did not result in any significant improvement in the dewaterability of the sludge. Also in Figure 9, the results show that the initial phosphate concentration in the supernatant of the anaerobic digested sludge ranged from 601.0 to 615.3 mg phosphorus/L, exhibiting a minor change across the wide range of polymer doses. However, by comparing Figure 7 with Figure 9, it can be seen that the phosphorus in the aqueous phase of the sludges was significantly reduced by the addition of the alum sludge, and the polymer dosing did not contribute to phosphorus removal from the aqueous phase of the sludges.

Figure 8—Images of mixed sludge (at ratio of 2:1) using Superfloc C2260 as a conditioner.

Figure 7—Dewatering behavior and supernatant phosphorus concentration of the mixed sludge (ratio = 2:1) with different doses of polymer Superfloc C2260 ($P =$ phosphorus).

Discussion

**Immobilization of Phosphorus in the Reject Water.** Various attempts to reuse alum sludge have been recently reviewed by Babatunde and Zhao (2007). Co-conditioning and dewatering of alum sludge and waste activated sludge has been studied, and the enhancement of sludge settling and dewatering with reduction in polymer dose through the co-conditioning strategy has also been reported (Lai and Liu, 2004). However, this study explored another prospective use of alum sludge, regarding its ability to immobilize phosphorus released from digested activated sludge when it is co-conditioned with alum sludge. It can be seen, from Figure 4, that alum sludge has a considerable phosphorus adsorption capacity, often described by the Langmuir isotherm or Freundlich isotherm in the literature (Dayton and Basta, 2005b; Dayton et al., 2003; Makris et al., 2005; Zhao and Babatunde, 2006). However, the results from this study found that the Freundlich isotherm fitted the data better than Langmuir isotherm. Unlike the Langmuir isotherm, the Freundlich isotherm does not interpret the adsorption phenomena, because it does not permit the calculation of the adsorption maxima. Nevertheless, the adsorption capacity exhibited by alum sludge is believed to be attributed to the aluminum in alum sludge (see Table 1), which has a strong affinity for phosphorus, and this has been demonstrated in many studies (Dayton and Basta, 2005a; Ippolito et al., 2003; Kim et al., 2002; Yang, Tomlinson, Kennedy, and Zhao, 2006). Although adsorption is considered a complicated process involving many physicochemical processes (Ippolito et al., 2003; Makris et al., 2005; Yang, Zhao, Babatunde, Wang, Ren, and Han, 2006), it is reasonable to believe that the addition of alum...
sludge resulted in the change of characteristics of the resultant sludge, which is closely related to the adsorption behavior. For example, the zeta potential of the sludge was significantly altered when a different amount of alum sludge was added, as shown in Figure 10. Initially, the zeta potential of the anaerobic digested sludge (refers to mix ratio 1:0 in Figure 10) was $-30.0$ to $-31.9$ mV, while that of the alum sludge (refers to mix ratio 0:1 in Figure 10) was $+14.2$ to $+18.5$ mV. The zeta potential of the mixed sludge increased with increased addition of the alum sludge. The values ranged from $-17.0$ to $-20.4$, $-15.1$ to $-16.3$, $-7.5$ to $+6.5$, and $+5.8$ to $+9.8$ mV at mix ratios of 3:1, 2.5:1, 2:1, and 1:1, respectively (see Figure 10). This highlights the change of the surface characteristics of the mixed sludge. The trend of increased zeta potential with increasing amount of alum sludge addition may be beneficial to phosphorus adsorption (Yang, Zhao, Babatunde, Wang, Ren, and Han, 2006b). It should be pointed out that the phosphorus adsorption capacity of alum sludge can be affected by various factors, including differences in the quality of the source water and the different treatment chemicals and processes in practice. Thus, alum sludges can significantly vary in their phosphorus-adsorption characteristics (Babatunde and Zhao, 2007; Dayton and Basta, 2005b; Makris et al., 2005). Nevertheless, regarding phosphorus immobilization through the co-conditioning of digested activated sludge and alum sludge, the results derived from the mix ratio of 2:1 in this study (see Figure 6) can be considered satisfactory.

During the phosphorus-adsorption process, the TOC and pH of the mixed sludge at different mix ratios were found to increase, as shown in Figure 11. The TOC in the supernatant of the anaerobic digested sludge ranged from 76.66 to 117.67 mg carbon/L, while that of the alum sludge ranged from 5.38 to 7.39 mg carbon/L. Interestingly, the TOC of mixed sludge did not lie between that of the two sludges. The increase of TOC in proportion to the increased addition of alum sludge suggests the possible release of TOC from the surface of the alum sludge, while phosphate is being adsorbed (Yang, Zhao, Babatunde, Wang, Ren, and Han, 2006b). Consequently, as more phosphate is adsorbed, more humic acid (in terms of TOC) may be exchanged and then released into the supernatant of the mixed sludge. This may be a drawback of the alum sludge co-conditioning strategy. Also in Figure 11, the pH of the anaerobic digested sludge ranged from 7.50 to 7.62, while the pH of the alum sludge ranged from 6.80 to 7.13. The pH range of the various mixtures were 7.50 to 7.62, 7.32 to 7.41, 7.14 to 7.32, and 6.86 to 7.14, corresponding to mix ratios of 3:1, 2.5:1, 2:1, and 1:1, respectively. Theoretically, the pH of the mixtures should be between the initial pH of the anaerobic sludge and that of the alum sludge. However, the pH of all the samples at the different mix ratio

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**Figure 9**—Dewatering behavior and the supernatant phosphorus concentration in anaerobic digested sludge with different doses of polymer Superfloc C2260 ($P = $ phosphorus).

**Figure 10**—Zeta potential of the mixed sludge at different mix ratios.

**Figure 11**—Increasing trend of pH and TOC in the supernatant of the mixed sludge during phosphate adsorption by the alum sludge.
was higher than the initial pH of the anaerobic digested sludge. This indicates that a hydroxide group (–OH), a functional group on the surface of the alum sludge, has been exchanged and released into the solution during the phosphate-adsorption process. The results from the change of TOC and pH in the adsorption system evidently suggest that ligand exchange seems to be the adsorption mechanism, as discussed in detail by Yang, Zhao, Babatunde, Wang, Ren, and Han (2006b).

The Role of Alum Sludge in Co-Conditioning Digested Activated Sludge. The inclusion of alum sludge in the anaerobic digested sludge can improve the dewaterability of the anaerobic digested sludge, because both the SRF and CST were reduced (see Figure 5). This may be attributed to a large portion of insoluble aluminum hydroxides in the alum sludge acting as a coagulant in chemical coagulation/flocculation. As an example, Guan et al. (2005) studied the feasibility of reusing alum sludge to enhance particulate pollutant removal in primary wastewater treatment. It was found that the removal efficiencies of suspended solids and COD were improved by 20 and 15%, respectively, at an alum sludge dose of 18 to 20 mg/L. It was claimed that floc sweeping and physical adsorption were the main mechanisms. More importantly, by comparing Figures 7 and 9, it becomes clear that a significant reduction of polymer dose can be achieved when alum sludge is involved in the digested sludge co-conditioning. A significant reduction of optimal polymer (Superfloc C2260) dose was demonstrated. The optimal polymer dose was reduced from 120 mg/L (when the digested sludge was conditioned alone) to 15 mg/L (when the digested sludge was co-conditioned with alum sludge at mix ratio of 2:1). This agreed with the findings reported by Lai and Liu (2004), who claimed a corresponding decrease in the required dosage of a cationic polyelectrolyte when alum sludge was co-conditioned with an activated sludge. Lai and Liu (2004) postulated that the alum sludge acted as a skeleton builder, making the mixed sludge more incompressible and rendering the dewatering process more effective. In this study, the dewaterability of the mixed sludge at different mix ratios (see Figure 5) was compared with the corresponding zeta potential of the sludge at the same mix ratios (see Figure 10). Although the sludge properties changed with the different mix ratios, the optimal mix ratio was characterized as 2:1 (anaerobic digested sludge:alum sludge), in which the zeta potential of the mixed sludges ranged from $\pm 7.5$ to $\pm 6.5$ mV (see Figure 10)—closer to zero than that in any other mix ratios. This reflects that the alum sludge acted in charge neutralization to improve the dewaterability of the anaerobic digested sludge.

A Case Analysis. The process described in Figure 12 details the proposed integration of alum sludge in co-conditioning and dewatering of the anaerobic digested sludge from a WWTP using the A²/O process for municipal wastewater treatment. The WWTP has a gravity belt thickener (GBT), which allows the thickening process to take place in several seconds, thus eliminating the occurrence of the anaerobic condition in the thickening process. Therefore, the release of phosphorus from the thickening process is successfully controlled. The average concentration of phosphate in the supernatant from the GBT is 1.1 mg phosphorus/L (see

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**Figure 12—Schematic of a proposed strategy of alum sludge co-conditioning with the anaerobic digested sludge of a municipal WWTP.**

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Figure 12). However, phosphorus is significantly released when the sludge is subjected to anaerobic digestion. The phosphate concentration in the filtrate of the anaerobic digested sludge after mechanical dewatering ranged from 597.3 to 674.5 mg phosphorus/L, with mean value of 603 mg phosphorus/L. Mass balance shows that the phosphorus in reject water, which is currently recycled to the beginning of the biological treatment system in the WWTP, is 113 mg phosphorus/L. If the alum sludge (moisture content of 95.12%) was introduced and mixed with the anaerobic digested sludge at a mix ratio of 2:1, according to the experimental result from this study, the computed phosphorus concentration in the reject water could be reduced from 113 to 1.21 mg phosphorus/L, as shown in Figure 12. A significant reduction of phosphorus load in the reject water is therefore achieved. Reduced phosphorus in the reject water may help to minimize the effect of the recycled phosphorus on effluent quality of the WWTP. The drawbacks of this proposal lie in (1) the potential increases of sludge cakes from the original amount of 13 000 to 20 000 kg/d when alum sludge is introduced, and (2) the increase of the quantity of the reject water with the hydraulic loading to the dewatering unit.

It should be noted that emphasis has always been placed on the likely disadvantages that may occur, rather than on the potential advantages that such co-conditioning strategy offers. Commonly cited disadvantages have included the fact that it is unlikely that a water treatment plant would be sited in close proximity to a wastewater treatment facility, which implies that the cost and economics of sludge transport/haulage might become a potential deciding factor. Nevertheless, co-conditioning of digested activated sludge with alum sludge offers some promise, particularly in reference to conditioning and dewaterability. There is also the potential benefit of phosphorus reduction in reject water, which eliminates the phosphorus loading in the wastewater treatment process when the reject water is recycled. From the technical point-of-view, this strategy is practicable. However, from a holistic point-of-view, the decision of whether to use the alum sludge as a co-conditioner should duly consider the capacity of the dewatering unit, process control capabilities, cost and economics of sludge transport and polymer savings, and the willingness to accept the sludge.

Conclusions
The outcome of this study has shown that sludge alum can be successfully used to co-condition the anaerobic digested sludge. The inclusion of alum sludge not only improves the dewaterability of the digested sludge, but it also beneficially enhanced phosphate removal from the reject water, thereby eliminating the potential phosphorus loading in the wastewater treatment process when the reject water is recycled. The major conclusions are as follows:

- The alum sludge (moisture content of 95.21%) has demonstrated a considerable ability for phosphorus adsorption. The adsorption behavior can be described using the Freundlich isotherm model.
- When alum sludge was introduced to co-conditioning and dewatering with anaerobic digested sludge, the optimal mix ratio, gauged by both the phosphate control in the reject water and the improvement of dewaterability of the resultant sludge, is 2:1 (anaerobic digested sludge:alum sludge, volume basis). According to this study, this will indicate a reduction of approximately 99% of phosphorus in recycled reject water.
- The addition of alum sludge to the anaerobic digested sludge improved the dewaterability of the anaerobic sludge. The optimal polymer (Superfloc C2260) dose for the anaerobic digested sludge was 120 mg/L, while the optimal dose for the mixed sludge (mix ratio 2:1) was 15 mg/L.
- The decision on the applicability or otherwise of the co-conditioning and dewatering strategy should include an integrated cost-effective evaluation of process capabilities, sludge transport, increased cake disposal, additional administration, polymer saving, and so on. However, the co-conditioning and dewatering strategy is practicable, from a technical point-of-view.

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