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1 **CO-CONDITIONING OF DIGESTED EXCESS ACTIVATED SLUDGE WITH ALUM**
2 **SLUDGE: BENEFIT OF PHOSPHORUS REDUCTION IN REJECT WATER**

3
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9
10
11 **ABSTRACT**

12
13 In this study, alum sludge was introduced into co-conditioning and dewatering with an anaerobic
14 digested activated sludge to examine the role of the alum sludge in improving the dewaterability
15 of the mixed sludge and also in immobilizing phosphorus in the reject water. Experiments have
16 demonstrated that the optimal mix ratio for the two sludges is 2:1 (anaerobic digested sludge :
17 alum sludge; volume basis), and this can bring about 99% phosphorus reduction in the reject
18 water through the adsorption of phosphorus by Al in the sludge. The phosphorus loading in
19 wastewater treatment plants is itself derived from the recycling of reject water during the
20 wastewater treatment process. Consequently, this co-conditioning and dewatering strategy can
21 achieve a significant reduction in phosphorus loading in wastewater treatment plants. In addition,
22 the use of the alum sludge can beneficially enhance the dewaterability of the resultant mixed
23 sludge by decreasing both the SRF and the CST, due to the alum sludge acting as a skeleton
24 builder. Experiments have also demonstrated that the optimal polymer (Superfloc C2260) dose
25 for the anaerobic digested sludge was 120 mg/l while the optimal dose for the mixed sludge (mix
26 ratio 2:1) was 15 mg/l, highlighting a huge saving in polymer addition. Therefore, from the
27 technical perspective, the co-conditioning and dewatering strategy can be viewed as a “win-win”
28 situation. However, for its full-scale application, integrated cost-effective analysis of process
29 capabilities, sludge transport, increased cake disposal, additional administration, polymer saving
30 etc. should be factored in.

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KEYWORDS

Adsorption, alum sludge, biological phosphorus removal, conditioning, anaerobic digested excess sludge, phosphorus removal, reject water

INTRODUCTION

As phosphorus is a limiting growth nutrient for algae in most receiving water bodies, it should be removed prior to 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 due to its lower costs and reliability for wastewater treatment (Horan, 1990; Tchobanoglous et al., 2003). In the BPR process, phosphorus in the influent is incorporated into 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, the phosphate is removed from BPR process through the excess activated sludge, which may contain phosphorus in the range of 3-6 percent (Sedlak, 1995) on a dry weight basis or 8-12.3 percent on volatile suspended solids (VSS) basis (Liu, 1995; Liu et al., 2000). This phosphorus enriched sludge is then generally thickened to reduce its volume and followed by anaerobic digestion to reduce the organic level. However, phosphorus can be released when bacteria that

1 contain stored phosphorus (i.e. PAOs) are subjected to anaerobic conditions, which include
2 thickening and/or anaerobic digestion, leading to a P-enriched supernatant and P-enriched filtrate
3 after the mechanical dewatering of the sludge (Jardin and Popel, 1994). Both the P-enriched
4 supernatant and the filtrate are termed as reject water. It has been recognized that the reject water
5 should be treated since its recycling to the wastewater treatment system will impair effluent
6 quality (Janus and Roest, 1997). Popel and Jardin (1993) reported a theoretical estimation that
7 the supernatant from the thickening process could potentially result in 5% phosphorus feed back
8 through reject water recycling. More significantly, under a normal operating condition of a BPR
9 process the phosphate release can theoretically result in 20% to 43% phosphorus feedback and
10 the possible P-feedback can reach up to 95% of the original P loading at a WWTP (Popel and
11 Jardin, 1993). Consequently, if the readily biodegradable chemical oxygen carbon (rbCOD) for
12 biological phosphorus removal is not sufficient, the return of the reject water with high level of
13 phosphorus can lead to reduced phosphorus removal efficiency of the BPR process
14 (Tchobanoglous et al., 2003).

15

16 In order to remove phosphorus from the recycled reject water, several attempts including
17 chemical addition to reduce phosphorus level have been made. Generally, lime, aluminium, iron
18 and magnesium salts can be used in similar ways as in standard chemical phosphorus
19 precipitation (Jenkins et al., 1971). This, however, can lead to increased operational cost and/or
20 sludge production, which may not favour its use. For this reason, other cost effective treatment
21 methods and materials are being investigated. Industrial by product, particularly those that
22 contain high levels of Al and/or Fe have been considered as cost-effective alternative to metal
23 salts to remove phosphorus from wastewater (Roques et al., 1991; Huang and Chiswell, 2000;

1 Kim et al., 2003). Recent studies have also focused on the reuse of aluminium-based drinking
2 water treatment sludge for phosphorus removal since it is an inescapable by-product during the
3 drinking water production and has exhibited a strong affinity for phosphorus (Makris et al., 2005;
4 Yang et al., 2006a; Razali et al., 2007).

5
6 One of the alternative uses of alum sludge is in the co-conditioning and dewatering with
7 anaerobic digested excess activated sludge. It is expected that alum sludge will be a potential
8 adsorbent for phosphorus immobilization in the reject water. Furthermore, co-conditioning of the
9 two kinds of sludges may reduce the polymer dose required to achieve good dewaterability, since
10 the alum sludge acts as a skeleton builder in the mixed sludge and thus has beneficial effect in
11 the dewatering process (Lai and Liu, 2004). In this study, an attempt was made to co-condition
12 and dewater anaerobic digested excess sludge with alum sludge for the purpose of exploring: (1)
13 the dewaterability of the mixed sludge under different mix ratios (2) the influence of alum sludge
14 addition on polymer dose during conditioning, and (3) the P reduction in reject water after
15 dewatering. Moreover, possible application of the results from this study to a wastewater
16 treatment plant (WWTP) in Dublin is discussed.

17

18 **MATERIALS and METHODS**

19

20 **Digested activated sludge and alum sludge.** The anaerobic digested excess sludge was
21 collected from the anaerobic digester unit of a WWTP located in northeast Dublin, Ireland. The
22 WWTP employs an anaerobic/anoxic/aerobic (A²/O) process for municipal wastewater treatment.
23 The anaerobic digested sludge contains 97.89% of water and about 603.0 mg-P/l of phosphate in

1 its supernatant. In order to examine the phosphorus in the solids phase of the sludge, a centrifuge
2 was used to separate the biosolids at 3000 rpm. The solids were then washed with distilled water
3 until the residual phosphate in the wash water was less than 0.05 mg-P/l. Thereafter, the solid
4 was dried at 103 ± 2 °C. The weighed solid was digested using the standard method of nitric acid
5 digestion (3030 E, APHA, 1992). The phosphate concentration in the solution of the nitric acid
6 digestion was measured.

7
8 The alum sludge with moisture content of 95.21% was collected from the holding tank of the
9 sludge dewatering unit of a Water Treatment Works in southwest Dublin, Ireland where
10 aluminium sulphate is used as coagulant and an cationic polymer (FO-4140 PWG) is employed
11 as coagulation aid treating a nearby reservoir water. Characterization of the alum sludge was
12 done by examining its physical and chemical properties. To examine the chemical components,
13 the alum sludge was subjected to a 103 ± 2 °C heating process. The solids obtained were then
14 digested and analysed using Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-
15 AES, IRIS Advantage), Ion Chromatography (DX-120) and TOC-V CSH (Shimadzu).

16
17 **Co-conditioning procedure.** Sludge conditioning tests were conducted using the digested
18 excess sludge and the mixed sludge (the mixed sludge refers to the mixture of the anaerobic
19 digested sludge and alum sludge at a mix ratio of 2:1;v/v, digested excess sludge: alum sludge).
20 The 2:1 mix ratio was determined as the optimal mix ratio that ensures the lowest phosphate
21 concentration in the supernatant with the least amount of alum sludge addition. A cationic
22 polyelectrolyte named Superfloc C2260 (CYTEC, Netherlands), which is a high molecular
23 weight polymer with a charge density of 40%, was employed as chemical conditioner. The

1 conditioning tests were performed using a jar-stirring device where the sludge was mixed with
2 the various polymer doses at a mean velocity gradient (G) value of 500 S^{-1} for 20 S, followed by
3 a reaction process which was at a G value of 34 S^{-1} for 294 S. This provides a GT value of 10000,
4 which is considered as the most critical determinant factor to ensure the shear conditions (Novak
5 and Lynch, 1990, Novak et al., 1993)

6

7 The dewaterability of the sludge was evaluated using the CST (capillary suction time) and SRF
8 (specific resistance to filtration). The CST was determined using a Triton CST Apparatus (Triton
9 W.P.R.L., Type 130) with a CST paper of size $7 \times 9 \text{ cm}$. SRF tests were performed using a
10 standard Buchner funnel with a Whatman No. 1 qualitative filter paper ($\phi 70 \text{ mm}$). A 50 kpa of
11 vacuum suction was applied. The images of the sludge appearance under polymer conditioning
12 were captured using an image acquisition system which consists of a Dell Workstation 400
13 equipped with an ICRGB frame grabber (Imaging Technology, US) and a CCD camera (XC-
14 003P, Sony).

15

16 **Phosphorus adsorption by alum sludge.** To determine the phosphorus adsorption capacity of
17 the alum sludge, series of batch stirring tests were conducted by adding pre-determined amount
18 of the liquid alum sludge to an artificial phosphate solution. The artificial phosphate solution was
19 prepared by dissolving pre-weighed potassium dihydrogen phosphate (KH_2PO_4) in distilled
20 water. The mixture was then adjusted to pH of 6.5, 7.0 and 7.5, using either sulphuric acid (0.01
21 M) or sodium hydroxide (0.1 M) to simulate the real pH range when digested sludge and alum
22 sludge were mixed. The mixture was then mechanically agitated to facilitate adsorption over a 6
23 h pre-determined equilibrium time. After adsorption, equilibrated samples were filtered using

1 0.45 µm millipore filter paper (Millipore) and analysed for phosphate concentration. Phosphate
2 concentrations and pH values were determined using the stannous chloride method (4500-P D,
3 APHA, 1992) and a pH meter (WTW, pH 325), respectively.

4
5 Equilibrium data were fitted with Freundlich model in the form of (Tchobanoglous et al., 2003):

$$7 \lg\left(\frac{x}{m}\right) = \lg K_f + \frac{1}{n} \lg C_e \quad (1)$$

8
9 where x/m is the mass of adsorbate adsorbed per unit mass of adsorbent, mg-P/g-sludge; K_f is the
10 Freundlich capacity factor, (mg-P/g-sludge) (l-water/mg-P)^{1/n}; C_e is the equilibrium
11 concentration of adsorbate in solution after adsorption, mg-P/l; $1/n$ is the Freundlich intensity
12 parameter. By plotting $\lg(x/m)$ versus $\lg C_e$, the constants in the Freundlich isotherm can be
13 obtained. In this study, the adsorption capacity was calculated at the equilibrium concentration
14 (C_e) of 1.0 mg-P/l. All were repeated twice and the average value of measurements was reported.

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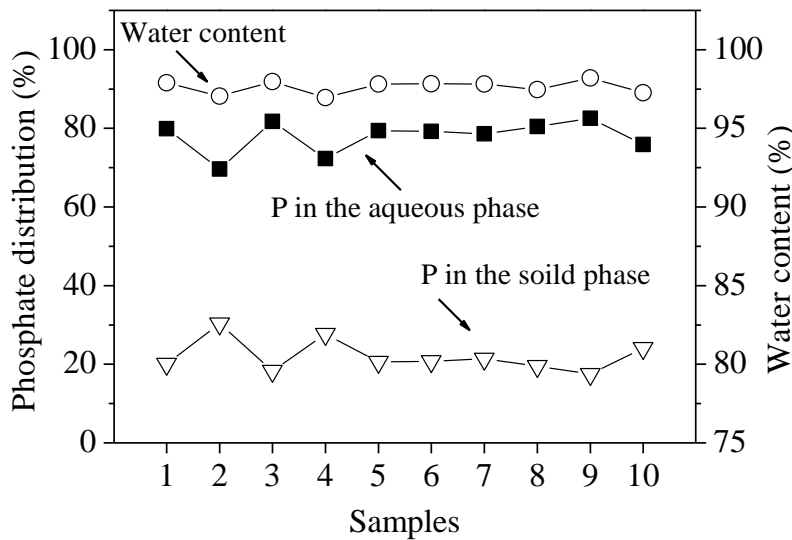
17 **RESULTS**

18

19 **Characteristics of the sludges: – The anaerobic digested excess sludge.** Figure 1 shows that
20 the water content of the anaerobic digested sludge ranged from 96.95% to 98.21% with an
21 average of 97.89%. The phosphate in the anaerobic digested sludge is distributed into two
22 phases, which are aqueous phase (representing the phosphate in the supernatant) and the solid
23 phase (representing the phosphate in the sludge solid). 78% of phosphate is distributed within the

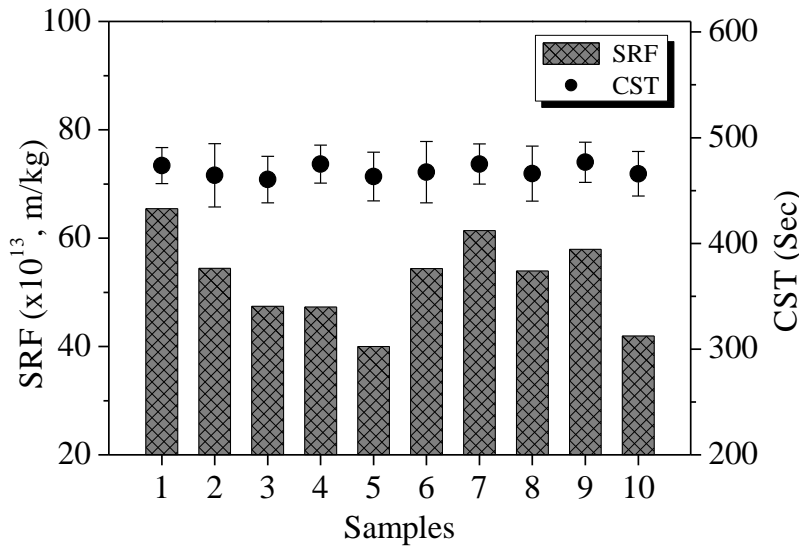
1 aqueous phase while 22% of the phosphate is distributed within the solid phase. Thus it is
 2 believed that phosphate in the reject water is derived predominantly from the supernatant of the
 3 anaerobic digested sludge. Therefore, to reduce the phosphate level during the recycling of the
 4 reject water to the wastewater treatment process, the focus should be placed on the phosphate in
 5 the aqueous phase of the anaerobic digested sludge.

6
 7 The CST and SRF of the anaerobic digested sludge are illustrated in Figure 2. From the samples
 8 tested, the CST ranged from 463.3 seconds to 473.6 seconds while the SRF ranged from
 9 40.01×10^{13} m/kg to 65.43×10^{13} m/kg. Although all the sludge samples were from the same
 10 source, their CST and SRF values showed some variation. This could be attributed to the
 11 operating conditions including sludge transfer and storage methods of the WWTP (Nissen and
 12 Vesilind, 1974). From Figure 2, the dewaterability of the sludge can be adjudged as poor.



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 15
 16 **Figure 1 - Water content and phosphate distribution in different samples of the anaerobic**
 17 **digested excess sludge**

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4 **Figure 2 - SRF and CST of the anaerobic digested sludge**

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6 **Characteristics of the sludges: – The alum sludge.** The physical and chemical properties of the

7 alum sludge are shown in Table 1. The sludge contains 95.21% of water while the solid content

8 is 4.79%. The alum sludge contains 194.49 mg-Al/g-sludge (dried at $103 \pm 2^\circ\text{C}$) or 0.93% (by

9 mass) as aluminium, indicating that aluminium is the dominating component. The other principal

10 chemical component is natural organic matter (NOM), such as humic acid, expressed as TOC,

11 which is 118.44 mg-C/g-sludge.

12

13 Figure 3 illustrates the values of CST and SRF of the alum sludge. The CST ranged from 169.8

14 to 197.2 seconds while the SRF ranged from 1.99×10^{13} to 4.14×10^{13} m/kg. In comparison with

15 the results presented in Figure 2, it becomes clear that the alum sludge exhibited better

16 dewaterability than that of the anaerobic digested sludge.

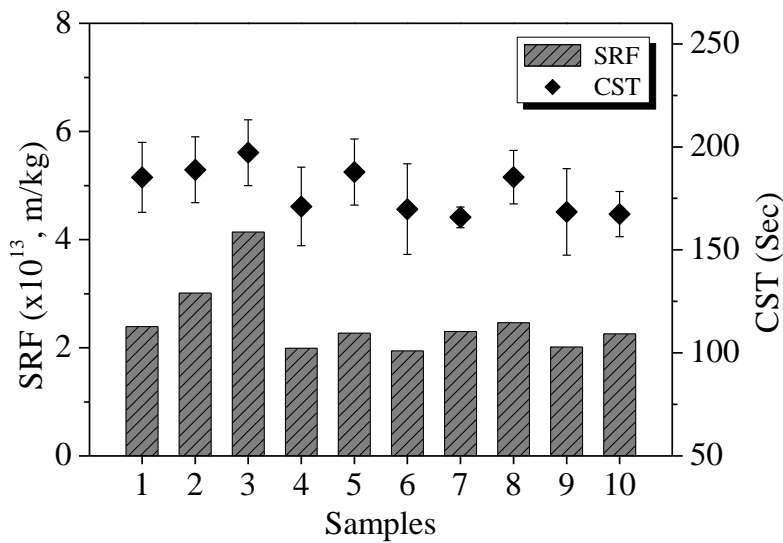
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2 **Table 1 - The physical and chemical properties the alum sludge**

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Properties	Unit	Average	±SD, n=3
pH	—	6.14	0.01
Water content	% (at 103±2 °C)	95.21	0.09
Aluminium	mg-Al/g-sludge	194.49	0.51
Iron	mg-Fe/g-sludge	5.20	0.13
Calcium	mg-Ca/g-sludge	5.18	0.18
Magnesium	mg-Mg/g-sludge	1.59	0.05
Humic acid (as TOC)	mg-C/g-sludge	118.44	3.47
Cl ⁻	mg-Cl/g-sludge	11.39	0.74
SO ₄ ²⁻	mg-SO ₄ ²⁻ /g-sludge	8.86	0.49
Silicon	mg-Si/g-sludge	6.79	0.48

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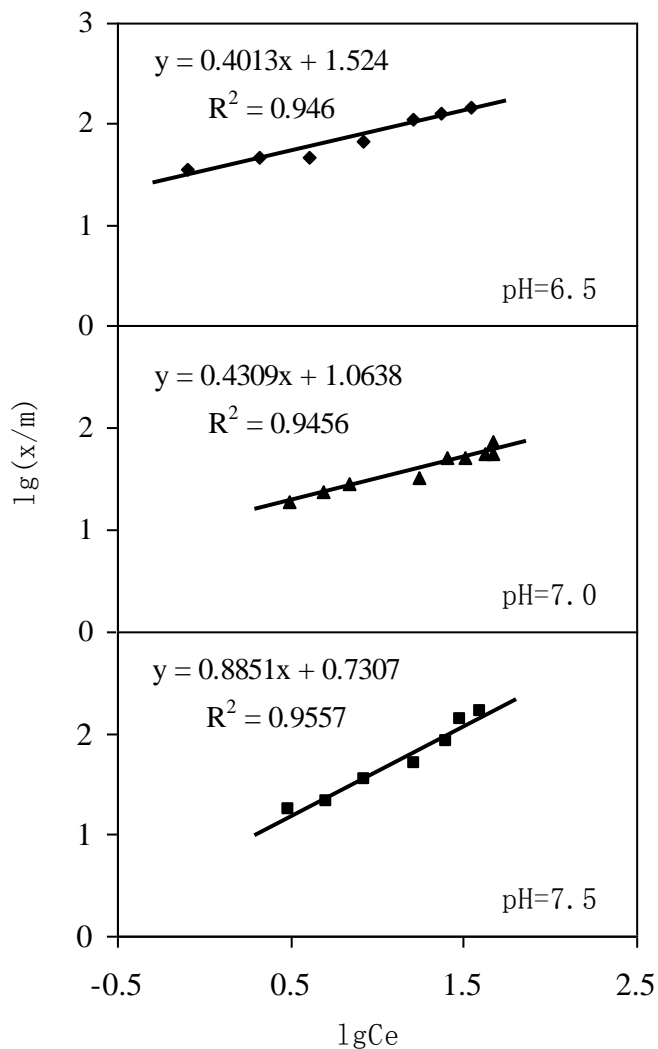


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Figure 3 - SRF and CST of the alum sludge

Figure 4 shows the adsorption isotherms of phosphate adsorbed onto the alum sludge at different pH conditions. The adsorption capacity was calculated using the Freundlich isotherm model (see equation (1)) at equilibrium concentration of 1.0 mg-P/l. The adsorption capacity increased from 5.38 to 33.4 mg-P/g-alum sludge when pH was decreased from 7.5 to 6.5. This indicates that the capacity is pH dependent, with the adsorption favoured at low pH.



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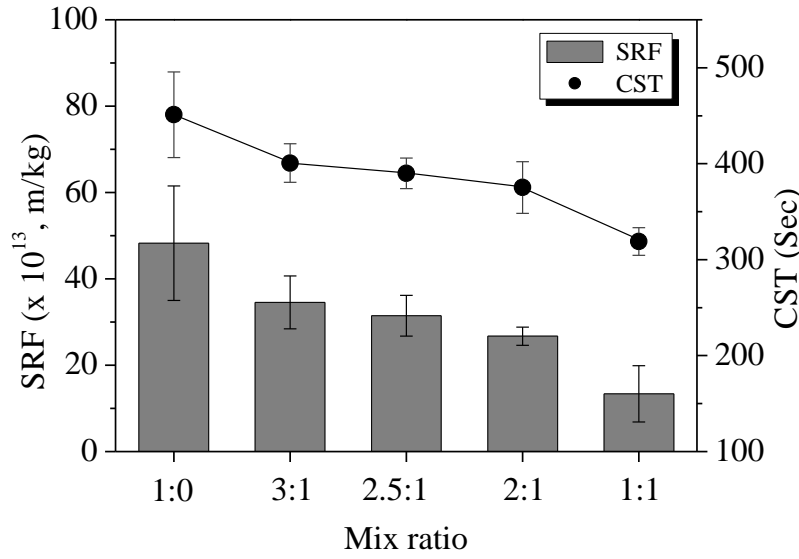
Figure 4 - Adsorption isotherms of phosphate adsorbed onto the alum sludge at different pH conditions

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 as well as the supernatant phosphorus concentration of the mixed sludge were measured. The results are shown in Figure 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 increasing amount of alum sludge addition. The SRF of the anaerobic sludge was decreased from 48.3×10^{13} to 13.4×10^{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-P/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-P/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

1 unit in the WWTP, the optimal mix ratio was chosen as 2:1 for the ensuing sludge conditioning
2 tests using organic polymer as conditioner.

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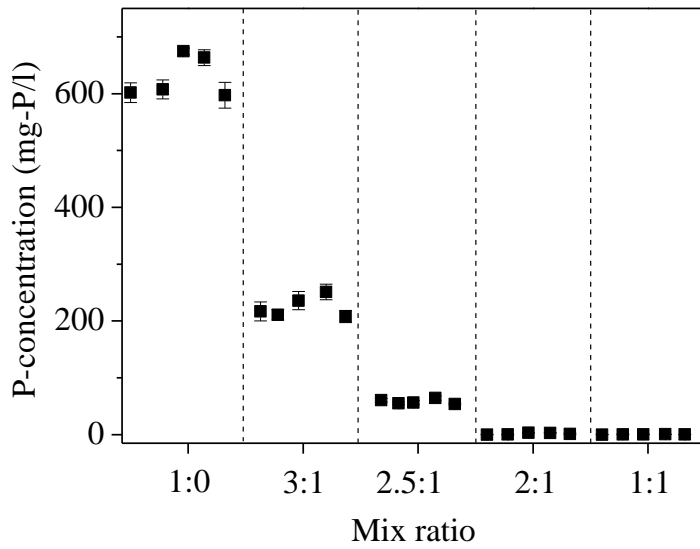


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6 **Figure 5 - Dewaterability of the mixed sludge at different mix ratios**

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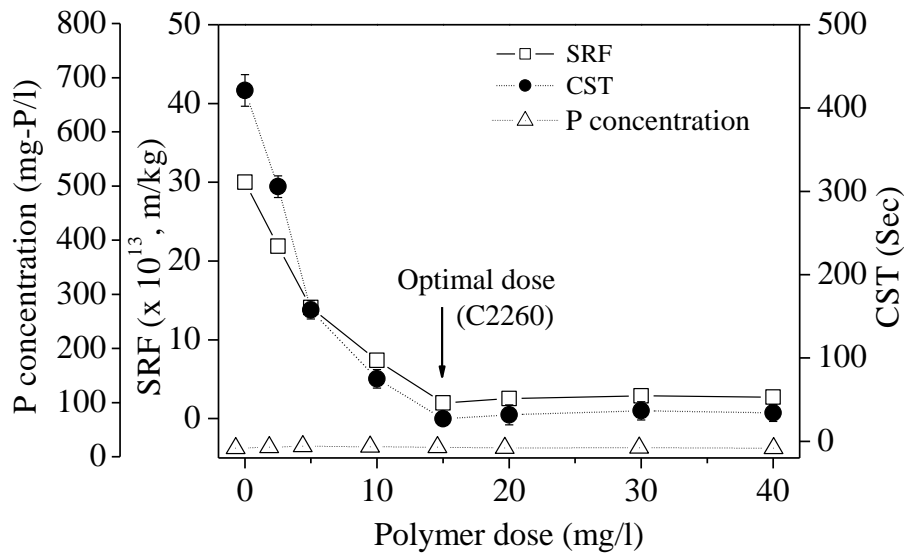
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1 **Figure 6 - Determining the optimal mix ratio of digested sludge and alum sludge**

2

3 **Polymer conditioning of the mixed sludge.** Figure 7 shows the dewatering behaviour of the
4 mixed sludge (at ratio of 2:1) conditioned by a cationic polyacryamide Superfloc C2260. The
5 phosphorus concentration in the supernatant of the mixed sludge during the conditioning process
6 is also jointly illustrated in the figure. The results show that the polymer conditioning results in a
7 significant improvement of the mixed sludge dewaterability as evaluated by SRF and CST. The
8 values of SRF and CST decreased from 30.01×10^{13} to 2.74×10^{13} m/kg and from 421 to 33.9
9 seconds respectively, while polymer dose was increased from 0 to 15 mg/l. The optimal polymer
10 dose for the mixed sludge was determined to be 15 mg/l since further increase of polymer dose
11 beyond that value did not bring about any further decrease of SRF or CST as shown in Figure 7.
12 In addition, Figure 7 shows that the phosphate concentration in the supernatant was very low at
13 all the different polymer doses, ranging from 0.15 to 3.1 mg-P/l.

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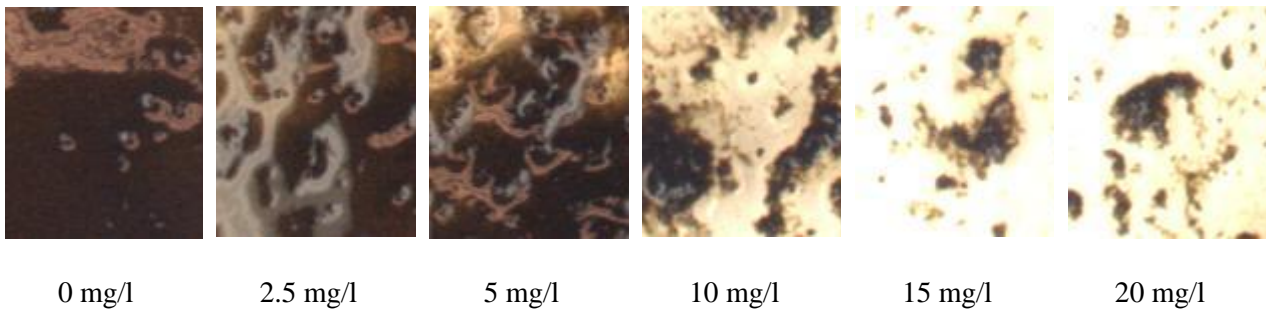


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1 **Figure7 - Dewatering behaviour and supernatant P-concentration of the mixed sludge**
2 **(ratio=2:1) with different dose of polymer Superfloc C2260**

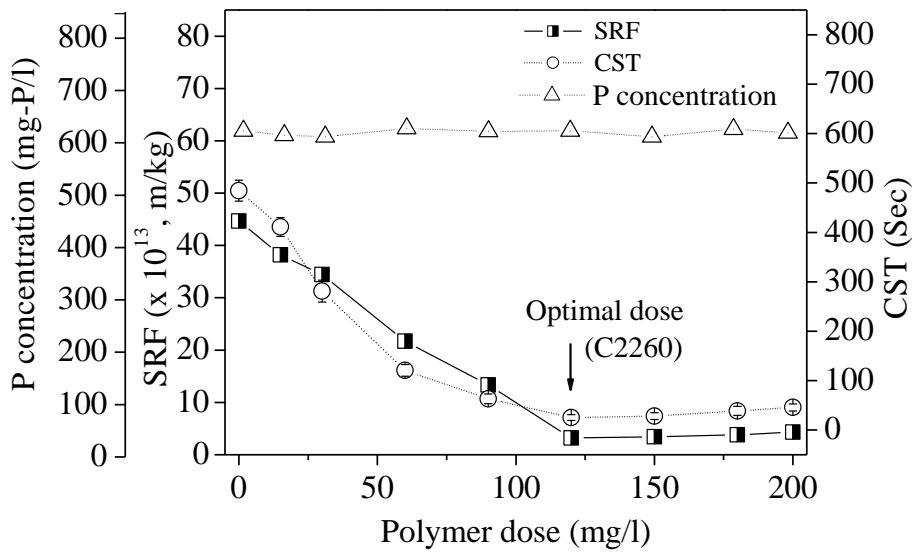
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4 Figure 8 shows images of the mixed sludge (mix ratio 2:1) at various doses of Superfloc C2260
5 during conditioning. Although the captured images represent the qualitative description of the
6 sludge at the specific conditions in this study, the change of sludge appearance in terms of
7 particle aggregation/floc and free water released, with increased polymer dose can be clearly
8 seen.



12 As a comparison, Figure 9 provides evidence to illustrate the changes of SRF and CST with
13 various doses of polymer (Superfloc C2260) for the digested sludge only. The values of SRF
14 decreased from 44.65×10^{13} to 3.21×10^{13} m/kg and CST decreased from 484.4 to 25.3 seconds
15 with increasing polymer dose up to 120 mg/l. However, it is interesting to note that large amount
16 of polymer was added and the optimal dose was 120 mg/l, which corresponds to the least SRF
17 and CST values as illustrated in Figure 8. Increasing the polymer dose beyond the optimal dose
18 did not result in any significant improvement in the dewaterability of the sludge. Also in Figure 9,
19 the results show that the initial phosphate concentration in the supernatant of the anaerobic

1 digested sludge ranged from 601.0 to 615.3 mg-P/l, exhibiting a minor change across the wide
 2 range of polymer doses. However, by comparing Figure 7 and Figure 9, it can be seen that the
 3 phosphorus in the aqueous phase of the sludges was significantly reduced by the alum sludge and
 4 the polymer dosing did not contribute to phosphorus removal from the aqueous phase of the
 5 sludges.

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9 **Figure 9 - Dewatering behaviour and the supernatant P-concentration in anaerobic**
 10 **digested sludge with different dose of polymer Superfloc C2260**

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13 **DISCUSSION**

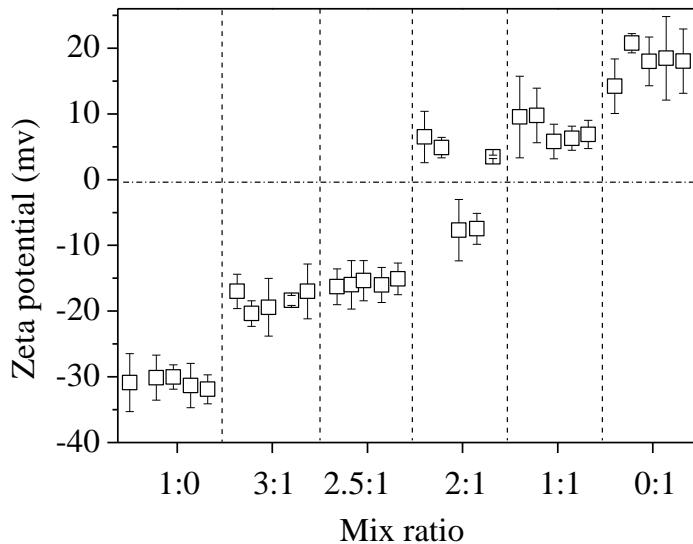
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15 **Immobilization of phosphorus in the reject water.** Various attempts to reuse alum sludge have
 16 been recently reviewed by Babatunde and Zhao (2007). Co-conditioning and dewatering of alum

1 sludge and waste activated sludge has been studied, and the enhancement of sludge settling and
2 dewatering together with reduction in polymer dose through the co-conditioning strategy has also
3 been reported (Lai and Liu, 2004). However, this study explored another prospective use of alum
4 sludge as regards its ability to immobilize phosphorus released from digested activated sludge
5 when it is co-conditioned with alum sludge. It can be seen from Figure 4 that alum sludge has a
6 considerable phosphorus adsorption capacity that is often described by Langmuir isotherm or
7 Freundlich isotherm in the literature (Dayton et al., 2003; Dayton and Basta, 2005a; Makris et al.,
8 2005; Zhao and Babatunde, 2006). However, the results from this study found that the
9 Freundlich isotherm fitted the data better than Langmuir isotherm. Unlike the Langmuir isotherm,
10 the Freundlich isotherm does not interpret the adsorption phenomena since it does not permit the
11 calculation of the adsorption maxima. Nevertheless, the adsorption capacity exhibited by alum
12 sludge is believed to be attributed to Al in alum sludge (see Table 1) which has a strong affinity
13 for phosphorus and this has been demonstrated in many studies (Ippolito et al., 2003; Kim et al.,
14 2003; Dayton and Basta, 2005b; Yang et al., 2006a). Although adsorption is considered as a
15 complicated process involving many physico-chemical processes (Ippolito et al., 2003; Makris et
16 al., 2005; Yang et al., 2006b), it is reasonable to believe that the addition of alum sludge resulted
17 in the change of the characteristics of the resultant sludge, which is closely related to the
18 adsorption behaviour. For example, the zeta potential of the sludge was significantly altered
19 when different amount of alum sludge was added, as shown in Figure 10. Initially, the zeta
20 potential of the anaerobic digested sludge (refers to mix ratio 1:0 in Figure 10) was -30.0 to $-$
21 31.9 mV while that of the alum sludge (refers to mix ratio 0:1 in Figure 10) was $+14.2$ to $+18.5$
22 mV. The zeta potential of the mixed sludge increased with increased addition of the alum sludge,
23 The zeta potential values ranged from -17.0 to -20.4 , -15.1 to -16.3 , -7.5 to $+6.5$ and from $+5.8$

1 to +9.8 mV at mix ratios of 3:1, 2.5:1, 2:1 and 1:1, respectively (see Figure 10). This highlights
2 the change of the surface characteristics of the mixed sludge. The trend of increased zeta
3 potential with increasing amount of alum sludge addition may be beneficial to phosphorus
4 adsorption (Yang et al., 2006b). It should be pointed out that the P-adsorption capacity of alum
5 sludge can be affected by various factors including differences in the quality of the source water,
6 and the different treatment chemicals and processes in practice. Thus alum sludge can
7 significantly vary in their P-adsorption characteristics (Dayton and Basta, 2005a; Makris et al.,
8 2005; Babatunde and Zhao, 2007). Nevertheless, as regards phosphorus immobilization through
9 the co-conditioning of digested activated sludge and alum sludge, the results derived from the
10 mix ratio of 2:1 in this study (see Figure 6) can be considered satisfactory.

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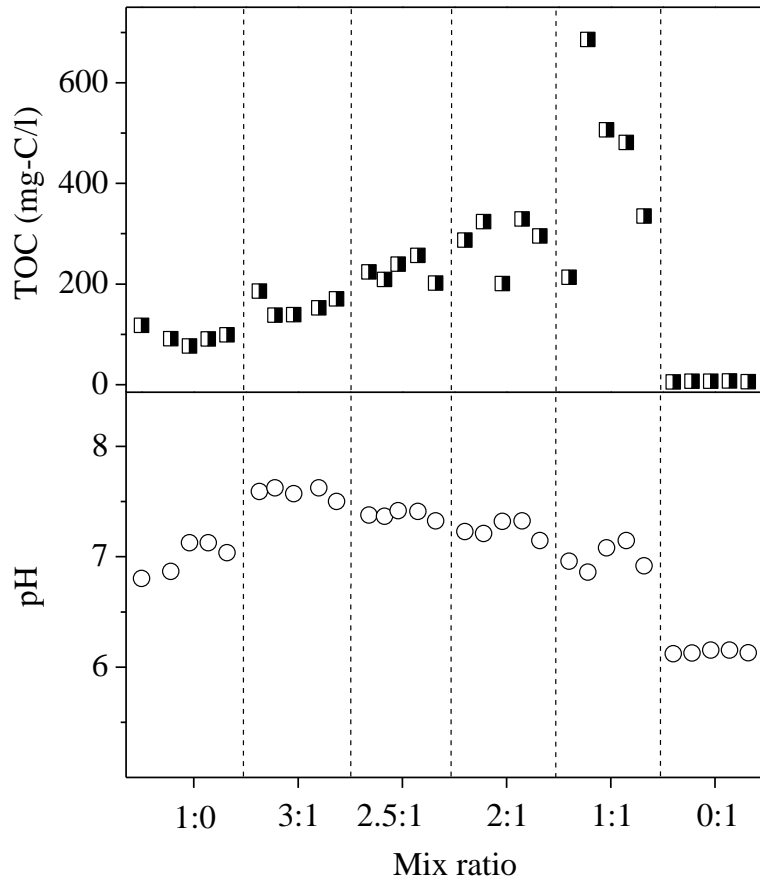
14 **Figure 10 - Zeta potential of the mixed sludge at different mix ratio**

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16 During the P-adsorption process, the TOC and pH of the mixed sludge at different mix ratios
17 were found to increase as shown in Figure 11. The TOC in the supernatant of the anaerobic

1 digested sludge ranged from 76.66 to 117.67 mg-C/l while that of the alum sludge ranged from
2 5.38 to 7.39 mg-C/l. Interestingly, the TOC of mixed sludge did not lie between that of the two
3 sludges. The increase of TOC in proportion to the increased addition of alum sludge indicates the
4 release of TOC from the surface of the alum sludge while phosphate is being adsorbed (Yang et
5 al. 2006b). Consequently, as more phosphate is adsorbed, more humic acid (in terms of TOC) is
6 exchanged and released into the supernatant of the mixed sludge. This may be a drawback of the
7 alum sludge co-conditioning strategy. Also in Figure 11, the pH of the anaerobic digested sludge
8 ranged from 6.80 to 7.13 while the pH of the alum sludge ranged from 6.12 to 6.15. The pH
9 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
10 corresponding to mix ratios of 3:1, 2.5:1, 2:1 and 1:1, respectively. Theoretically, the pH of the
11 mixtures should be between the initial pH of the anaerobic sludge and that of the alum sludge.
12 However, the pH of all the samples at the different mix ratio was higher than the initial pH of the
13 anaerobic digested sludge. This indicates that $-OH$, a functional group on the surface of the
14 alum sludge, has been exchanged and released into the solution during the phosphate adsorption
15 process. The results from the change of TOC and pH in the adsorption system evidently show
16 that ligand-exchange is the dominating adsorption mechanism as discussed in detail by Yang et
17 al. (2006b).

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Figure 11 - Increasing trend of pH and TOC in the supernatant of the mixed sludge during phosphate adsorption by the alum sludge

The role of alum sludge in co-conditioning digested activated sludge. The inclusion of alum sludge in digested excess sludge can improve the dewaterability of the anaerobic digested sludge since both SRF and CST were reduced (see Figure 5). This may be attributed to a large portion of insoluble aluminium 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 sewage treatment. It was found that the removal efficiencies of SS and COD were improved by 20% and 15% respectively, at an

1 alum sludge dose of 18–20 mg Al/l. It was claimed that floc-sweeping and physical adsorption
2 were the main mechanisms. More importantly, by comparing Figures 7 and 9, it becomes clear
3 that a significant reduction of polymer dose can be achieved when alum sludge is involved in the
4 digested sludge co-conditioning. A significant reduction of optimal polymer (Superfloc C2260)
5 dose was demonstrated. The optimal polymer dose was reduced from 120 mg/l (when the
6 digested sludge was conditioned alone) to 15 mg/l (when the digested sludge was co-conditioned
7 with alum sludge at mix ratio of 2:1). This result confirms the experimental findings reported by
8 Lai and Liu (2004) who claimed a corresponding decrease in the required dosage of a cationic
9 polyelectrolyte when alum sludge was co-conditioned with an activated sludge. It was postulated
10 that the alum sludge acted as a skeleton builder, making the mixed sludge more incompressible
11 and rendering the dewatering process more effective.

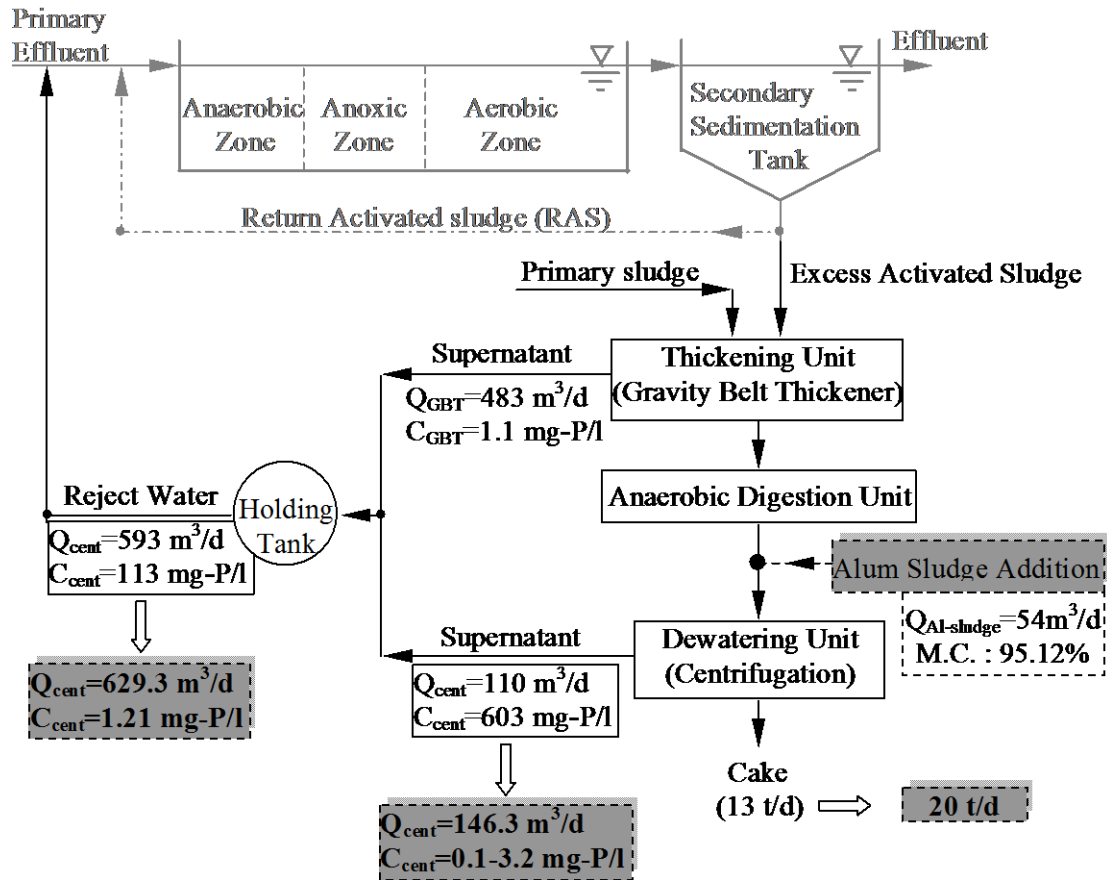
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13 **A case analysis.** The process described in Figure 12 below details the proposed integration of
14 alum sludge in co-conditioning and dewatering of digested excess activated sludge from a
15 WWTP employing the A²/O process for municipal wastewater treatment. The WWTP has a
16 gravity belt thickener (GBT), which allows the thickening process to take place in several
17 seconds, thus eliminating the occurrence of the anaerobic condition in the thickening process.
18 Therefore, the release of P from the thickening process is successfully controlled. The average
19 concentration of phosphate in the supernatant from the GBT is 1.1 mg-P/l (see Figure 12).
20 However, phosphorus is significantly released when the excess sludge is subjected to anaerobic
21 digestion. The phosphate concentration in the filtrate of the anaerobic digested sludge after
22 mechanical dewatering ranged from 597.3 to 674.5 mg-P/l, with mean value of 603 mg-P/l. Mass
23 balance shows that the phosphorus in reject water, which is currently recycled to the beginning

1 of the biological treatment system in the WWTP, is 113 mg-P/l. If the alum sludge (moisture
2 content of 95.12%) was introduced and mixed with the anaerobic digested sludge at a mix ratio
3 of 2:1, according to the experimental result from this study, the computed phosphorus
4 concentration in the reject water could be reduced from 113 to 1.21 mg-P/l, as shown in Figure
5 12. A significant reduction of phosphorus load in the reject water is therefore achieved. Reduced
6 phosphorus in the reject water may help to minimize the impact of the recycled phosphorus on
7 effluent quality of the WWTP. The drawbacks of this proposal lie in: (1) the potential increases
8 of sludge cakes from original amount of 13 to 20 t/d when alum sludge is introduced; (2) the
9 increase of the quantity of the reject water together with the hydraulic loading to the dewatering
10 unit.

11
12 It should be noted that emphasis has always been placed on the likely disadvantages that may
13 occur, rather than on the potential advantages that such co-conditioning strategy offers.
14 Commonly cited disadvantages have included the fact that it is unlikely that a water treatment
15 plant would be sited in close proximity to a wastewater treatment facility, which implies that the
16 cost and economics of sludge transport/haulage might become a potential deciding factor.
17 Nevertheless, co-conditioning of digested activated sludge with alum sludge offers some promise
18 particularly in reference to conditioning and dewaterability. There is also the potential benefit of
19 phosphorus reduction in reject water, which eliminates the P loading in wastewater treatment
20 process when the reject water is recycled. From the technical point of view, this strategy is
21 practicable. However, from a wholistic point of view, the decision to use the alum sludge as a co-
22 conditioner or not should duly consider the capacity of the dewatering unit, process control

1 capabilities, cost and economics of sludge transport and polymer savings, and also the
 2 willingness to accept the sludge.

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6 **Figure 12 - Schematic of a proposed strategy of alum sludge co-conditioning with the**
 7 **anaerobic digested sludge of a WWTP**

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9

10 **CONCLUSIONS**

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

6

- 7 ● The alum sludge (moisture content of 95.21%) has demonstrated a considerable ability for
8 phosphorus adsorption. The adsorption behaviour can be described using Freundlich isotherm
9 model.
- 10 ● When alum sludge was introduced to co-conditioning and dewatering with digested activated
11 sludge, the optimal mix ratio gauged by both the phosphate control in reject water and the
12 improvement of dewaterability of the resultant sludge is 2:1(anaerobic digested sludge : alum
13 sludge, volume basis). According to this study, this will expect a reduction of about 99% of
14 phosphorus in recycled reject water.
- 15 ● The addition of alum sludge to the anaerobic digested sludge improved the dewaterability of the
16 anaerobic sludge. The optimal polymer (Superfloc C2260) dose for the anaerobic sludge was 120
17 mg/l while the optimal dose for the mixed sludge (mix ratio 2:1) was 15 mg/l.
- 18 ● The decision on the applicability or otherwise of the co-conditioning and dewatering strategy
19 should in case include an integrated cost-effective evaluation of process capabilities, sludge
20 transport, increased cake disposal, additional administration, and polymer saving etc. However,
21 the co-conditioning and dewatering strategy is practicable from technical point of view.

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2

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