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# Benefit of lignite as a filter aid for dewatering of digested sewage sludge demonstrated in pilot scale trials

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ABSTRACT

Lignite, a low-rank coal, was investigated as a filter aid for the dewatering of digested sewage sludge at a pilot scale using a plate-and-frame filter press. When the lignite was used to condition the sludge at solids mass ratios of 0.5 to 1 and 1 to 1, the Net Sludge Yield ($Y_N$) was found to increase from 1.2 kg m$^{-2}$ h$^{-1}$ without lignite conditioning to 5.2 and 7.8 kg m$^{-2}$ h$^{-1}$, respectively. Higher doses of the lignite did not result in further increases in the sludge yield due to the low mass fraction of the sludge solids in the cake. The filterability of lignite-conditioned sludge as affected by the flocculant dose was evaluated using Specific Resistance to Filtration (SRF) as well as percentage sludge water removal and product solids content. Flocculation using ZETAG7501 at 19 kg/tonne reduced the SRF from $5.8 \times 10^{13}$ at 11 kg/tonne to $9.3 \times 10^{12}$. Using the high molecular weight polymer ZETAG8125 at 13 kg/tonne achieved similar sludge water removal compared with using ZETAG7501 at 19 kg/tonne and even lower specific resistance. The improvement in sludge dewaterability by lignite conditioning confirmed the results from laboratory scale studies.

## 1. Introduction

Sludge is a by-product of wastewater treatment operations. Large quantities of sludge produced worldwide together with new and strengthened regulations on sludge disposal present a continual challenge for the water industry to seek more efficient sludge treatment and disposal approaches with lower environmental impact. One of the most important aspects of sludge treatment prior to disposal is the reduction of sludge volume by water separation and thus the reduction of transportation and handling costs.

Sewage sludge is a colloidal system and, compared to sludge from some industrial processes, it is very difficult to dewater due to the high organic content in the sludge solids. During mechanical dewatering by pressure or vacuum filtration, filter medium blinding [1] and cake blinding often occur, which in turn decreases the cake porosity and increases the cake specific resistance [2–4]. The use of chemical conditioners, such as organic flocculants, is found to increase the rate of sludge dewatering to a certain extent by reducing the sludge specific resistance, but further increase of the rate and filter cake solids is still difficult [5,6], as following cake growth the high compressibility of the flocculated sludge results in sludge cake particles being easily deformed under pressure, which causes cake void closure and a subsequent reduction in sludge filterability [5,7]. Compressibility is a measure of the relative volume change of a sludge cake as a response to a pressure change. The efficiency of the overall dewatering process is therefore compromised by the need for longer compression time or higher pressures to achieve higher solid content.

Physical conditioners are sometimes used to reduce the compressibility of the sludge solids and improve the mechanical strength and permeability of the solid cake during compression. For the processes using high pressure and long filtration time (e.g. using a filter press), these physical conditioners are particularly efficient, forming a permeable and more rigid lattice structure which can remain porous under high pressure [8]. These materials are often called skeleton builders or filter aids, because of their role in building up the structural strength of the sludge solids and in assisting in filtration. While both carbon-based materials such as char [5,9], coal fines [9] and, most recently, lignite [10] as well as carbonaceous waste [11–14] and mineral materials including industrial materials and waste such as fly ash [15–19], cement kiln dust [13], lime [8,15] and gypsum [20,21] have all been investigated and proved to be able to enhance sludge dewaterability, carbon-based materials have the advantages of being able to add calorific value when the final solid product is used as fuel. A majority of the investigations have been carried out using small laboratory-scale vacuum or pressure filtrations.

Lignite, a low-rank coal, from Victoria, Australia is a cheap and abundant energy resource attracting great interests in its alterna-

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**Table 1**
Characteristics of sludge and lignite.

| | pH | Conductivity (mS cm$^{-1}$) | Total solids (%) | Suspended solids (%) | Ash content (% db[a]) | Total surface area (m$^2$ kg$^{-1}$, db) | Gross calorific value (MJ kg$^{-1}$, db) |
|---|---|---|---|---|---|---|---|
| Sludge | 7–8 | 5–6 | 1.6–2.0 | 1.2–1.3 | 29.7 | N/A | 16.6 |
| Lignite | 3–4[b] | 0.5–1[b] | 43–45 | N/A | 6.2 | 234 | 24.9 |

[a] db, dry basis.
[b] Value for water slurry.

tive industrial and agricultural use. Laboratory-scale investigations by this research group proved that Victorian lignite played an important role as a filter aid in enhancing the dewaterability of anaerobic digested sludge [10]. Based on the results of the laboratory study, the objectives of this study were: (1) to demonstrate the benefit of lignite conditioning for sewage sludge dewatering at a larger scale using a plate-and-frame filter press and (2) to determine the effects of the polyelectrolyte dose and the lignite dose on sludge dewatering behaviour using the filter press.

## 2. Materials and methods

### 2.1. Materials

Anaerobic digested sludge from a municipal wastewater treatment plant in Victoria, Australia was used in this study. To minimize the microbial activity after collection, the sludge was stored at 4 °C. A desired amount (50–90 L) was removed from the refrigerator 3 to 4 h before each test and was allowed to warm to around 18 °C in a 120 L stainless steel tank. It was also homogenised by stirring before each test.

Raw lignite was obtained from the Loy Yang mine in the Latrobe Valley, Victoria. The samples were milled and sieved to less than 1 mm particle size. Immediately before each test, the lignite was slurried by mixing a desired mass of lignite with the same mass of water in a 40 L tank.

The main characteristics of the sludge and the lignite are presented in Table 1.

Two linear cationic polyelectrolytes ZETAG7501 and ZETAG8125 supplied by Ciba Specialty Chemicals (Australia) were used to flocculate the sludge samples. The flocculants are copolymers of polyacrylamide and quaternised N, N-dimethylaminoethyl acrylate methylene chloride. ZETAG7501 has a low molecular weight and a high charge density, while ZETAG8125 has high molecular weight and low charge density. Table 2 lists the major characteristics of the two polyelectrolytes obtained from the manufacturer. Precise molecular weight information is not available. Conventionally, polymers are regarded as having low, medium or high molecular weight corresponding to molecular weight values in the ranges of $10^5$, $10^5$–$10^6$ and >$10^6$, respectively [22].

A 0.2 wt% flocculant solution was prepared by dissolving the polyelectrolyte powder in water and stirring for a further 2–3 h prior to use.

### 2.2. Sludge conditioning and dewatering

A sketch of the sludge dewatering process is presented in Fig. 1. The filter press is a Netzsch plate-and-frame filter press equipped with 16 plates (470 mm × 470 mm). Each side of the plate has a 25 mm depression. The maximum operating pressure is 7 bars (g). Three plates with monofilament polypropylene filter cloths (~40 μm) mounted on the face of each plate were used in this study.

**Table 2**
Characteristics of Zetag polyelectrolytes.

| | Effective pH range | Cationic character (Mole%) | Molecular weight range |
|---|---|---|---|
| Zetag7501 | 4–11 | 100 | Medium/low |
| Zetag8125 | 4–9 | ~24 | High |

The sludge sample in the 120 L tank was homogenised by stirring using a Lightnin open tank mixer (Fig. 1). The mixer consists of two sets of A310 high performance three blade impellers of 160 mm diameter mounted on the shaft 240 mm apart. Two or three small samples (~200 g) of the sludge were collected and weighed before being dried in an oven at 105 °C overnight for solids content analysis. Flocculation of the sludge was then carried out by adding a desired amount of the 0.2 wt% polyelectrolyte solution slowly into the tank while maintaining a stirring speed of 300–400 rpm. The mixture was further stirred for about 2 min while being closely observed for the condition of flocculation. For the tests using lignite as a conditioner, after the addition of the polyelectrolyte solution, the stirring speed was reduced to about 100 rpm, after which a desired amount of the lignite slurry (8–10 kg) was added to the flocculated sludge and mixed at the slower stirring speed for a further 60 s.

After settling for approximately 2–5 min while preparing for pumping, the mixture was pumped to the filter press by a diaphragm pump and the content in the holding tank was periodically stirred gently without breaking the flocs to avoid excessive settling. At the initial stage the pumping rate was controlled by adjusting the air pressure to the diaphragm pump. As the pressure built up inside the filter chambers, the pumping rate reduced over time. The pressure profiles during the dewatering process are shown in Fig. 2. The filtrate forced through the weave in the filter cloth was collected and weighed periodically during the process. For the tests with high dewatering rate (optimum flocculation with lignite conditioning), the filtration process was terminated when the mass of the filtrate collected over a period of 10 min was 0.1–0.5 kg. When the dewatering rate was low for the tests without lignite conditioning or under-flocculated, the runs were stopped after 3–4 h. After the pressure was released, the solid cakes inside each chamber were removed from the filter cloth and weighed. The solids were homogenised prior to sampling for moisture content measurements.

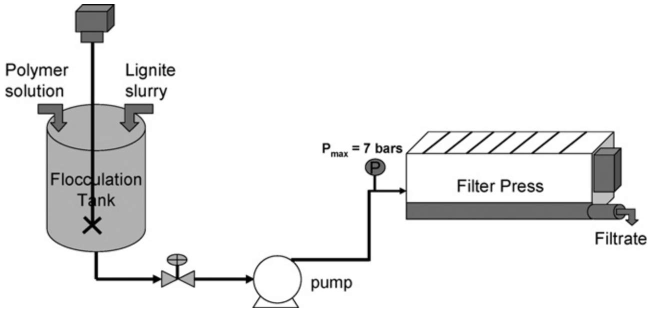

**Fig. 1.** A sketch of the experimental set-up for sludge dewatering tests using a filter press.

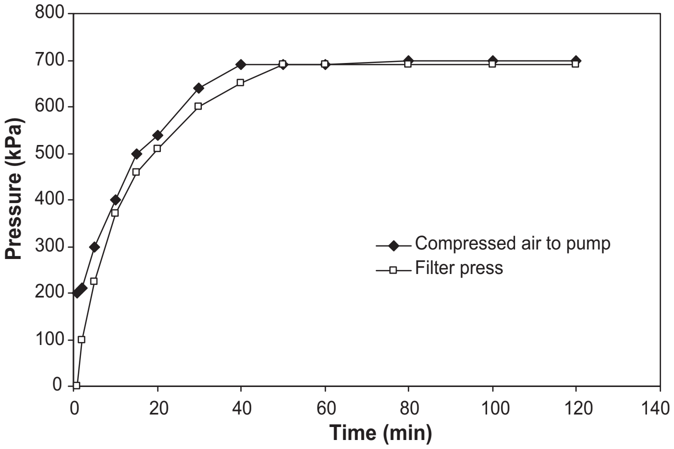

**Fig. 2.** Pressure profiles during sludge dewatering using the filter press.

### 2.3. Evaluation of sludge dewatering performance

Sludge dewatering performance can be assessed by measuring the amount of water removed and the solids content of the dewatered cake. The net percentage sludge water removal at time *t*, SWR(*t*), is determined using Eq. (1).

$$\mathrm{SWR}_{(t)}(\%)=\left(\frac{m_{F(t)}-m_W}{m_S-m_{SS}}\right)\times 100 \tag{1}$$

$m_{F(t)}$ (kg) is the mass of the filtrate at time *t*; $m_W$ (kg) is the total mass of extra water added including that for making up the polymer solution and the lignite slurry; $m_S$ (kg) is the total mass of the sludge at the start and $m_{SS}$ (kg) is the mass of sludge solids.

The total solids content at time *t* is calculated based on water removal results using Eq. (2).

$$\text{Total solids content}_{(t)}\,(\%)=\frac{m_{SS}+m_{LS}}{m_S+m_L-(m_{F(t)}-m_W)}\times 100 \tag{2}$$

where $m_{LS}$ (kg) is the mass of lignite solids and $m_L$ (kg) is the total mass of raw lignite.

Sludge filterability is often characterised by Specific Resistance to Filtration (SRF, m kg$^{-1}$), which is associated with the slope of the plot of $t/V$ vs $V$. Eq. (3), as used by Novak et al. [2], is a simplified form derived from the conventional filtration theory based on Darcy's law [23,24].

$$\frac{t}{V}=\frac{\mu \mathrm{SRF} w}{2PA^2}V+\frac{\mu R_m}{PA} \tag{3}$$

where *t* is the filtration time (s), *V* is the filtrate volume at time *t* (m$^3$), $\mu$ is the viscosity of filtrate (normally taken as the viscosity of water, 0.001 N s m$^{-2}$ at 20 °C), *w* is the mass of cake solids deposited per unit volume of filtrate (kg m$^{-3}$), *P* is the compression pressure (N m$^{-2}$), *A* is the filtration cross-section area (m$^2$) and $R_m$ is the resistance associated with the filter medium (m$^{-1}$).

In such cases where the applied pressure drop is gradually increased from a low value preceding the constant pressure period, Svarovsky [25] has used an equation starting from a point ($t_s$, $V_s$) which corresponds to the time and filtrate volume at the beginning of the constant pressure period.

$$\frac{(t-t_s)}{(V-V_s)}=\frac{\mu \mathrm{SRF} w}{2PA^2}(V+V_s)+\frac{\mu R_m}{PA} \tag{4}$$

If *a* is the slope of the linear plot of $(t-t_s)/(V-V_s)$ vs $(V+V_s)$, SRF can be determined using Eq. (5).

$$\mathrm{SRF}=\frac{2PA^2 a}{\mu w} \tag{5}$$

The Net Sludge Yield, $Y_{\mathrm{N}}$, can be used to evaluate the sludge dewatering efficiency without accounting for the solids added to the system by the physical conditioner. The yield at 90% of filtration completion, $Y_{\mathrm{N90}}$ (kg m$^{-2}$ h$^{-1}$) proposed by Zall et al. [8] can be calculated using Eq. (6). By plotting the rate of filtration (m$^3$ m$^{-2}$ h$^{-1}$) against the volume of filtrate (m$^3$), the linear portion of the curve is extrapolated to yield $V_\infty$, the ultimate volume of filtrate assuming all filterable water is pressed out. The status of 90% of completion occurs when 90% of $V_\infty$ is collected.

$$Y_{\mathrm{N90}}=\frac{V_{S90}R_S}{T_{90}A} \tag{6}$$

$$V_{S90}=V_{F90}+V_p \tag{7}$$

where $V_{S90}$ is the total volume of conditioned sludge filtered at 90% of completion (m$^3$), $V_{F90}$ is the volume of filtrate collected at 90% of completion, $V_p$ is the total volume of filter press chambers (m$^3$), $R_S$ is the sludge solids per unit volume of conditioned sludge (kg m$^{-3}$) and $T_{90}$ is the time to filter to 90% of completion.

## 3. Results

### 3.1. Effect of polyelectrolyte dose on sludge dewaterability

Based on the optimum polymer dose range obtained from laboratory studies [26], the effect of the polyelectrolyte dose on sludge dewatering rate using the filter press was investigated in the presence of the lignite as a physical conditioner. For flocculation, the polyelectrolyte ZETAG7501 that gave the highest sludge water removal in laboratory tests was chosen. Without any treatment the sludge was unfilterable. Without lignite conditioning, the filterability of under-flocculated sludge was found to be very poor. Therefore, in these tests, the lignite was added to aid the sludge dewatering at a solids mass ratio of lignite to sludge of 2 to 1.

Sludge water removal profiles using different amounts of ZETAG7501 are presented in Fig. 3a. All profiles exhibit a sharp increase in the initial stage of filtration followed by a gradual increase at a later stage before reaching a plateau, except for the 11.4 kg/tonne case which shows a much lower water removal and slower increase with time. As the profiles for the higher dose tests are too close to each other, a log–log plot is shown in Fig. 3b for a better view. A dose of 11.4 kg/tonne of sludge solids, which is in the range of the optimum dose for ZETAG7501 (10–11 kg/tonne) determined by laboratory-scale vacuum filtration tests [26], gave the lowest dewatering rate. An increase of the polymer dose to 18.8 kg/tonne increased the sludge water removal rate considerably. A further increase of the polymer dose to 23.8 kg/tonne led to an increase in dewatering rate at the initial stage, while at the later stage the dewatering rates at the three higher doses were similar. The profiles for 23.8 and 24.1 kg/tonne are overlapped.

This effect of polyelectrolyte dose on sludge dewatering rate can be further demonstrated by plotting the sludge water removal or total solids content at a selected time against the polymer dose as shown in Fig. 4. The total solids deposited at time *t* are calculated based on Eq. (2), while the final solids content results are the measured values of the final solids products. The time marked above each final solid content data point indicates the total run time of the test.

Results in Fig. 4 also show that an increase in the polymer dose from 11.4 to 18.8 kg/tonne resulted in the most significant improvement in water removal and solids content. As the polymer dosage increased to above 18.8 kg/tonne, the sludge water removal and corresponding solids content were slightly increased. A longer filtration time at a lower polymer dose led to a total solids content close to that achieved in less time, but using a higher polymer dose.

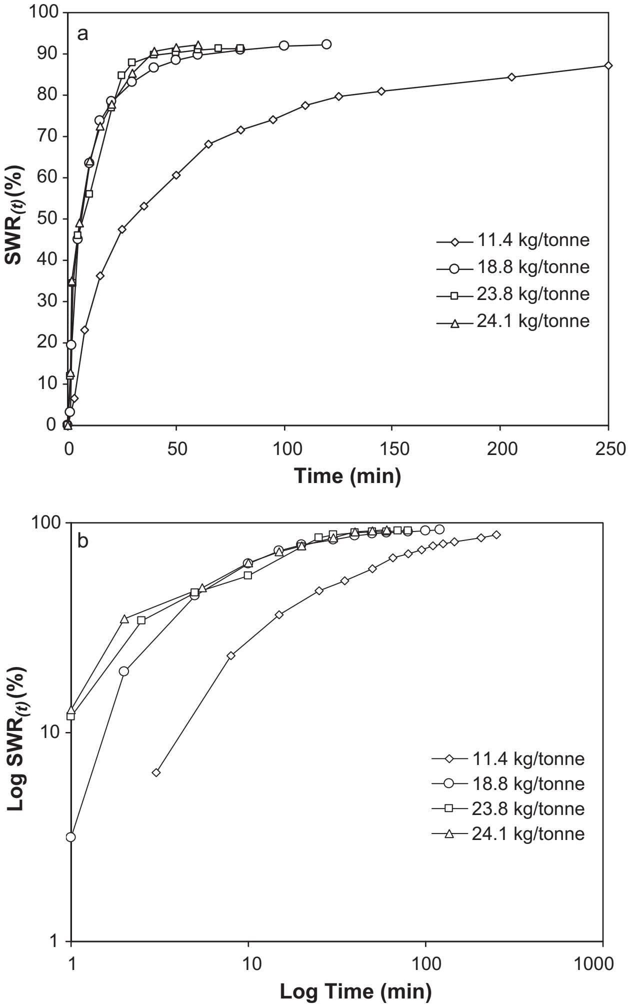

**Fig. 3.** Sludge water removal profiles at different polyelectrolyte doses (ZETAG7501; lignite to sludge solids mass ratio 2 to 1). (a) $SWR_{(t)}$% vs time; (b) Log $SWR_{(t)}$% vs Log time.

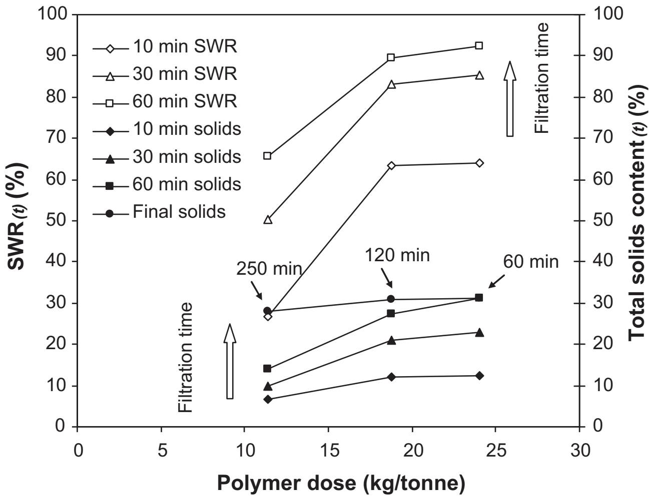

**Fig. 4.** Effect of polymer dose on sludge water removal and total solids content (ZETAG7501; lignite to sludge solids mass ratio 2 to 1).

**Table 3**
Specific Resistance to Filtration for sludge flocculated using ZETAG7501 and ZETAG8125 (2:1 lignite solids to sludge solids).

| | Polymer dose (kg/tonne) | $SRF \times 10^{12}$ (m kg$^{-1}$) |
|---|---|---|
| ZETAG7501 | 11.4 | 58 |
| | 18.8 | 9.3 |
| | 23.8 | 9.8 |
| | 24.1 | 10 |
| ZETAG8125 | 13.3 | 5.4 |
| | 13.5 | 5.4 |

The effect of the polymer dose on the rate of dewatering can also be demonstrated using the Specific Resistance to Filtration, SRF (Table 3). SRF, a commonly reported parameter for the evaluation of sludge filterability, is associated with the filtration rate. A lower SRF suggests better filterability. The calculation of SRF is based on Eq. (4), which is adjusted for the change in filtration pressure during the tests (as shown in Fig. 2), instead of the commonly used Eq. (3) for constant pressure.

When the dose of the polymer increased from 11.4 kg/tonne to 18.8 kg/tonne, SRF was significantly reduced from $58 \times 10^{12}$ to $9.3 \times 10^{12}$ m kg$^{-1}$, but any further increase in polymer dose did not lead to further reductions in the specific resistance.

Based on Figs. 3 and 4, the slight increase in the total solids content and water removal when the polymer dose was increased from 18.8 to 24 kg/tonne suggests an optimum dose between 18.8 and 24 kg/tonne. But the specific resistance results imply an optimum dose possibly even lower than 18.8 kg/tonne. Taking into consideration the cost of the polymer, for an industrial process the dose of 18.8 kg/tonne or lower rather than 24 kg/tonne is probably the economic optimum.

### 3.2. Comparison of two types of polyelectrolyte

For an industrial flocculation process, the typical dosage of Zetag polyelectrolytes recommended by the manufacturer is 2–10 kg/tonne dry solids. A flocculant dose at about 20 kg/tonne sludge solids would be considered high and possibly uneconomic. According to the laboratory-scale study of the ZETAG series polyelectrolytes [26], ZETAG7650, a discontinued product with high molecular weight, had the lowest optimum dosage for sewage sludge flocculation. ZETAG8125, which is an equivalent polymer to ZETAG7650 with a similar charge density and molecular weight, was selected to compare with ZETAG7501 for their dewatering performance. A dose of around  kg/tonne, the upper limit of the recommended dose range, was tested.

Sludge dewatering profiles using the two polymers are compared in Fig. 5a and as log–log plots in Fig. 5b. The curve for 23.9 kg/tonne ZETAG7501 is obtained by averaging the results for 23.8 and 24.1 kg/tonne, while that for ZETAG8125 is an average of the results for doses of 13.3 and 13.5 kg/tonne. The differences are shown as error bars. Fig. 6 compares the total solids content at selected filtration times using the two polymers. Differences are shown as error bars.

The results demonstrate that, although at the initial filtration stage the dewatering efficiency using ZETAG8125 at 13 kg/tonne was slightly lower than that using ZETAG7501 at 18.8 and 23.9 kg/tonne, at a later stage ZETAGE8125 achieved similar dewatering performance compared to ZETAG7501. However, the dose of ZETAG8125 was significantly lower than ZETAG7501, as can be seen in Fig. 5a. Similarly, after the initial stage producing slightly lower solids content using ZETAG8125, at 60 min the differences in total solids content between the tests using ZETAG8125 and higher doses of ZETAG7501 were within experimental error (Fig. 6).

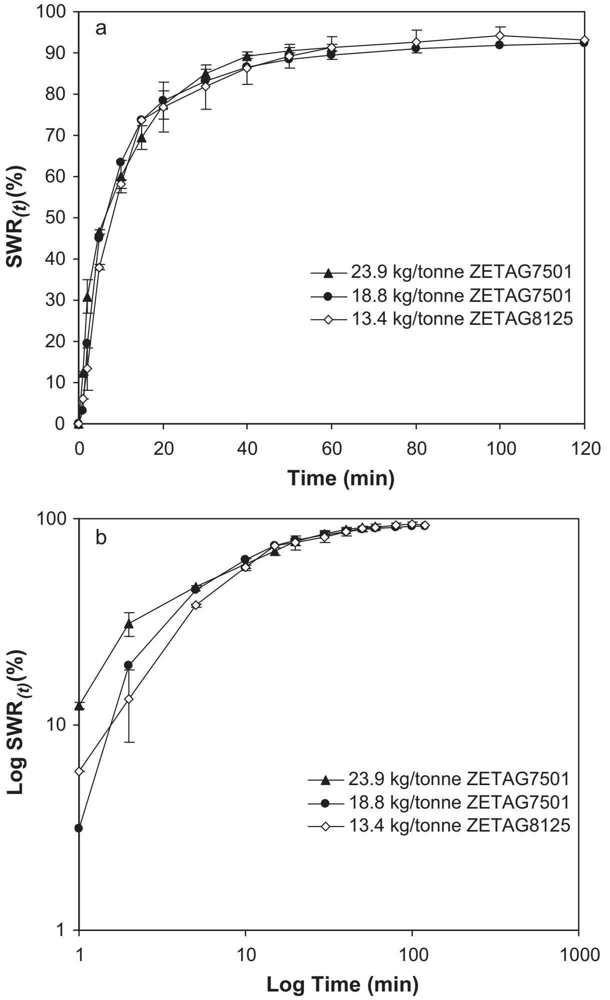

**Fig. 5.** Comparison of sludge water removal profiles using ZETAG7501 and ZETAG8125 (lignite to sludge solids mass ratio 2 to 1). (a) $SWR_{(t)}$% vs time; (b) Log $SWR_{(t)}$% vs Log time.

SRF results (Table 3) further confirm that ZETAG8125 at a much lower dose gave similar flocculation performance to ZETAG7501. Sludge flocculated using ZETAG8125 gave even lower SRF than using ZETAG7501. This result is in agreement with that from the laboratory scale tests that the optimum dosage of polyelectrolytes with higher molecular weight can be much lower than those with lower molecular weight [26].

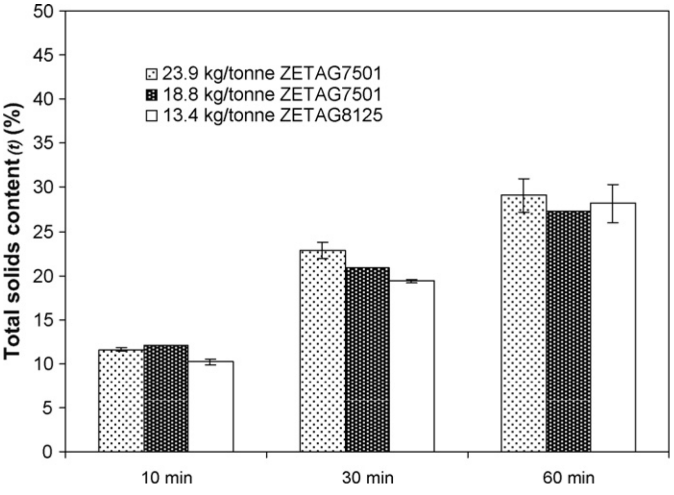

**Fig. 6.** Comparison of total solids content during dewatering using ZETAG7501 and ZETAG8125 (lignite to sludge solids mass ratio 2 to 1).

**Table 4**
Net Sludge Yield at different solids mass ratios of lignite to sludge (ZETAG7501).

| Lignite to sludge solids mass ratio | 0 | 0.51 | 0.99 | 1.7 |
|---|---|---|---|---|
| Polymer dose (kg/tonne) | 26.9 | 23.5 | 21.9 | 21.1 |
| $Y_{N90}$ ($kg\,m^{-2}\,h^{-1}$) | 1.2 | 5.2 | 7.8 | 7.4 |

### 3.3. *Evaluation of sludge dewaterability improved by lignite conditioning*

The effect of lignite to sludge solids mass ratio on dewatering rate was investigated by flocculating the sludge with the optimum dose of ZETAG7501 and conditioning with the lignite at different lignite to sludge solids ratios.

Net Sludge Yield ($Y_N$) is used to identify the effect of the lignite conditioning on sludge dewaterability. The results of $Y_{N90}$ calculated using Eqs. (6) and (7) are presented in Table 4.

As the solids mass ratio of lignite to sludge increased from 0 to 0.5 and 1, $Y_{N90}$ increased almost proportionally from 1.2 to 5.2 and 7.8 $kg\,m^{-2}\,h^{-1}$, respectively. Increasing the mass ratio to 1.7 the yield slightly reduced, which was likely to be due to the high fraction of the lignite solids in the total cake solids. Although the total solids yield may be higher, the sludge solids for this case represented a very low fraction in the cake. This gives an optimum lignite to sludge solids mass ratio of 1 to 1.

The improvement in sludge yield achieved using the lignite as a physical conditioner (4.3 and 6.5 times the sludge yield without lignite conditioning) was significant compared with that of some of the previous studies using different types of skeleton builders. Zhao and Bache [21] conditioned alum sludge using gypsum at the ratio of 0.6 to 1 sludge solids and an organic polymer. The Net Sludge Yield increased only marginally from 1.62 to 1.69 $kg\,m^{-2}\,h^{-1}$. Lee et al. [14] used agricultural waste rice shell and rice bran combined with chitosan, an organic polymer, to condition a sludge from a brewery wastewater treatment plant. The biggest improvement they achieved was a yield 3.4 times of that using the polymer alone when using rice shell at 0.6 to 1 of the sludge solids. Using the same ratio of wood chips and wheat dregs combined with inorganic chemical conditioners, ferric chloride or alum, to dewater sludge from a wastewater treatment plant, Lin et al. [12] obtained an improvement from 2.3 to 3.9 $kg\,m^{-2}\,h^{-1}$ using wood chips and from 0.92 to 3.1 $kg\,m^{-2}\,h^{-1}$ using wheat dregs.

## 4. Discussion

### 4.1. *Evaluation of sludge dewatering using Net Sludge Yield*

When physical conditioners are used during sludge dewatering, where these conditioners have solids content similar or higher than the sludge solids content, the evaluation of sludge dewaterability requires caution. The presence and characteristics of the additional solid materials and their influence on the parameters used should be taken into consideration. When a physical conditioner is added at a high dose, the evaluation based on the volume of filtrate may not be an appropriate measure of the filtration rate. As Lin et al. [12] proposed, the water may permeate into the skeleton builders reducing the total amount of free water to be removed. This effect can be significant when the physical conditioner is added at high doses. Lee et al. [14] observed a decrease in the total volume of the filtrate after adding a physical conditioner.

In terms of using final cake solids content or moisture content as a measurement for improved degree of sludge dewatering, it should also be taken into account that the addition of the physical conditioners, which consist of mainly insoluble materials, naturally increases the solids content of the final product. The final cake solids content alone is inadequate to establish whether the extent of sludge dewatering is enhanced.

The limitation of using SRF to evaluate the performance of physical conditioners is also associated with the additional solids in the physical conditioners and the variations in total solids content while comparing the effect of the physical conditioner dose. SRF should only be used as a criterion to compare the cases when the sludge solids and total solids remain relatively constant. For instance, SRF can be successfully used as a measure in choosing the appropriate dose of chemical conditioners, as demonstrated in previous studies [2,6,27] and in Sections 3.1 and 3.2, or in comparing physical conditioners at low doses [14]. In the case of using physical conditioners when large amounts of the conditioner solids are added to sludge, a new slurry of higher solids content is produced which contains the original sludge solids plus the conditioner solids. As indicated by Benitez et al. [13], although the specific resistance of the new conditioned slurry may be lower and the removal rate of total solids by filtration higher, the removal rate of the original sludge solids will not necessarily be higher. Therefore, if large amounts of conditioner solids are added, a different measure is needed to express filterability.

Net Sludge Yield ($Y_N$) is the rate of sludge solids filtered per unit area per unit time. Instead of accounting for the total cake solids (e.g. $w$ in Eq. (5)), $Y_N$ considers only the sludge solids content ($R_S$), which therefore can better demonstrate the efficiency of sludge dewatering at the presence of high doses of physical conditioners as shown in previous studies [8,14,28] and in the present study.

### 4.2. *Sludge dewatering at a pilot scale*

Unlike a small lab-scale process, a pilot scale process generally has more process variables and is less easy to control. The result of the sludge dewatering is affected not only by conditions such as polymer and lignite doses, but also by variations such as the filtration pressure, stirring speed and time, sludge solids inconsistency, etc. between tests.

Comparing the results in this study to those from laboratory scale tests, the most significant difference is that a much higher dose of the organic polymer was required to achieve optimum dewatering in the pilot scale filter press process. As observed in laboratory scale tests [29], there are interactions between organic polymers and fine particles of the lignite during the sludge dewatering process. One of the reasons for the requirement of higher polymer dose could be that a greater proportion of lignite fines were created in the larger scale tests which inevitably consumed a more significant portion of the flocculant. Another reason for the higher optimum dose of the polyelectrolytes could be that the flocs were disintegrated due to the more severe mixing conditions needed and that extra polymer was needed to re-flocculate the sludge. Novak and Lynch [30] reported a similar effect of shear which required a higher dose of polymers for flocculation. This issue may be solved by in-line mixing in industrial processes. In addition, results from the tests using ZETAG8125 indicate that by choosing the right type of flocculants, the dosage of the flocculants can be considerably reduced and, thus, made more economic.

Another major difference is the variation in the filtration pressure over a period of time using the filter press for sludge dewatering compared to the often constant and easy to control pressure in laboratory scale tests. During the filter press dewatering process, two pressures were monitored: the input pressure of the compressed air to the diaphragm pump and the pressure at the inlet of the filter press. The pumping pressure could be adjusted by changing the pressure of the compressed air (maximum 7 bars) to the diaphragm pump, whilst the inlet pressure was not adjustable and reflected the pressure increase during the test as the solids accumulated inside the filter press chambers. As demonstrated in Fig. 2, the constant pressure phase occurred at a later stage of the process.

Other factors that are not easy to be kept constant are the actual polymer dose and the mass ratio of lignite to sludge solids. These are calculated based on sludge solids content, which was estimated from the average solid content of the batch and also the measured content from previous tests. The actual polymer dosage and lignite to sludge solids mass ratio were usually different from the intended values as the actual solids content of the sludge often varied for each test as shown in Table 4.

Therefore, further investigation may involve the evaluation and the selection of chemical conditioners which require lower dosage and the optimisation of the process and processing conditions for sludge dewatering at a larger scale using the lignite as a filter aid.

### 4.3. *Benefit of lignite as a physical conditioner or filter aid in sludge dewatering*

Research has found that the improved sludge dewaterability by the addition of a physical conditioner is due to the formation of a more rigid and porous and less compressible structure of the sludge solids in the presence of the physical conditioner.

Using the same Victorian lignite as in this study as a filter aid, laboratory tests revealed that the interactions between the negatively charged lignite particles and the cationic polyelectrolyte residues during dewatering occurred [29] and led to the formation of a filter cake with homogeneous and rigid solid structures, which had much higher permeability and porosity and lower compressibility than the sludge solids alone [10]. Similar observations of the interactions between chemical and physical conditioners in the presence of sludge colloids were also reported by Zhao and Bache [21,29]. When physical conditioners are used as the sole conditioner, the dose of the conditioners required in order to show a significant improvement in sludge yield can be very high [8], or the improvement is limited [11]. Sludge dewatering efficiency can achieve its optimum when physical conditioners are used in conjunction with chemical conditioners.

Carbon-based materials as physical conditioners are also advantageous over mineral physical conditioners in terms of their generally higher porosity, lower ash content and higher calorific value, such as the properties of the Victorian lignite shown in Table 1. High porosity is desirable characteristic for enhancing sludge dewaterability, while the high calorific value and low ash are very important properties when the dewatered solid product is eventually managed by incineration.

## 5. Conclusions

The benefit of lignite conditioning in sludge dewatering was demonstrated using a pilot scale filter press. It was found that the Victorian lignite was superior as a filter aid to improve the sludge dewaterability by increasing significantly the Net Sludge Yield. A pilot scale process was affected by more processing factors than a small scale laboratory process.

It was important to combine the dosing of organic flocculant with lignite conditioning to achieve optimum sludge dewatering. The dewatering rate and cake solids content were increased and the Specific Resistance to Filtration was effectively reduced as the dose of the polyelectrolyte was increased to the optimum. To achieve optimum sludge dewatering, the dose of polyelectrolyte ZETAG7501 required was considerably higher than that required in the laboratory scale tests. Using the high molecular weight polyelectrolyte ZETAG8125, a much lower dosage was able to achieve similar sludge dewatering results.

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