Ecological stabilization of thickened wastewater sludge from CAST process

Y. B. Cui, X. H. Wu, Zh. Sh. Liu, J. Zh. Liu and Y. Z. Lin

ABSTRACT

Wastewater sludge ecological stabilization (WWSES) pilot scale experiments were conducted for thickening treatment and disposal of sludge which came from Cyclic Activated Sludge Technology (CAST) process. The study was performed over the periods from June to November 2005 and from May to November 2006, on a bed of 80 m². The sludge loadings were stopped for the winter from December 2005 and resumed in May 2006. The results shows that dried sludge layer has higher permeation coefficients of 0.15–1.3 m/h. It is suggested that the percolate did not filtrate downwards evenly, part of percolate filtrates downwards along stems, roots and cracks existing in dried sludge which have lower flow resistance. The relationship of dried sludge thickness and operation time is in accord with quadratic equation under fluctuating sludge loadings. Linear regression equation can indicate dried sludge thickness variation under fixed sludge loading. In comparison with natural ones, coarse protein content of *Phragmites australis* roots in the system is twice as high, coarse fiber content of roots, coarse fat content of stems and leaf are obviously higher; and coarse protein content of *Typha augustifolia* in the system are obviously higher, while coarse fat and coarse fiber contents have no significant difference.

**Key words** | constructed wetland, percolated water, reed bed, sludge thicking, sludge dewatering

INTRODUCTION

Constructed wetlands have been used in China since the mid-1990s, and there are now more than 100 plants in operation for the purposes of municipal and industrial wastewater treatment, except for the sludge-drying reed bed. During last twenty to thirty years, interest has developed in using constructed wetlands (reed beds) to enhance conventional drying bed performance across some countries of Europe, North American and Asia (*Cooper et al. 1996; Burgoon et al. 1997; Kengne et al. 2006*).

The concept of wastewater sludge ecological stabilization (WWSES) was named herein, i.e., the ecological technology was used for sludge stabilization. The core of ecological stabilization is constructed wetland, commonly reed bed. The principal mechanisms of sludge ecological stabilization for drying the sludge more rapidly than old unplanted system are as follows (*Cooper et al. 2004*):

- stem, rhizomes and roots enhance water drainage by providing channels in depth;
- wind-rock produces holes in the sludge surface at the base of stems;
- evapotranspiration is enhanced by the presence of leaves;
- mineralization.

The aim of this research was to investigate the permeation performance, structure variation and thickness increase model of dried sludge in the reed bed, and plant components variation comparison between the wild and the constructed system.
SYSTEM DESCRIPTION AND METHODS

System description

A pilot-scale vertical flow constructed wetland (Figure 1) with a surface area of 80 m², having 60 cm sand-gravel matrix, supported by ventilated-drainage system and planted with *Phragmites australis* (common reed) in 2005 and about 25% of area planted with *Typha augustifolia* (cattail) in 2006, was fed with thickened sludge from a Cyclic Activated Sludge Technology (CAST) process, at the third wastewater treatment plant (WWTP) located in Changchun, a city of the Northeast of China. The substrata in constructed wetland unit comprise a 20 cm layer of large gravel, a 25 cm layer of small gravel, a 10 cm layer of fine sand, and 10 cm layer of coarse sand from bottom to top, while a freeboard of 0.5 m was allowed for accumulation of dewatered sludge. The drainage system consists of perforated PVC pipes with a diameter of 20 cm on the bottom, ventilation pipes with 10 cm diameter were mounted on the drainage pipes, extending 0.5 m over the matrix surface.

The thickened sludge from CAST process combines primary settling and secondary settling sludge, which has relatively lower VS/TS of averaged 34.7%. Characteristics of thickened sludge and loading are given in Table 1. During two years running, loaded sludge have a mean total solid (TS) of 22.34 g/L, volatile solid (VS) of 7.76 g/L and moisture content of 97%.

Sampling ports are set at the interface of the bottom of dried sludge layer and the surface of substrata for investigating the time of percolate filtrating dried sludge layer and at the bottom of the substrata for investigating the time of percolate filtrating constructed wetland substrata layer.

![Figure 1](https://iwaponline.com/wst/article-pdf/58/10/1911/435895/1911.pdf) | Constructed wetland sludge treatment system.

The permeation coefficient is calculated as follows:

Permeation coefficient = \( \frac{\text{the thickness of dried sludge layer (or substrata layer)}}{\text{filtration time}} \)

Operation and maintenance

Wetland was constructed before 1 June 2005. *Phragmites australis* harvested from nearby natural wetland were replanted in the unit on 2 June 2005 and watered with treated wastewater till plant length of 1.5 m, spending about forty days. Solids loadings were applied to the reed bed for two weeks from 12 to 25 July 2005 under the loading of 10 tons sludge per day, and then fourteen weeks from August to November 2005 under the loading of 10 tons per four days. Operated in a vertical flow mode, the sludge was uniformly distributed on the surface of the constructed wetland. The sludge loadings were stopped for the winter from December and resumed in May 2006.

The second year (2006) experiment was conducted from May to November, and was divided into three stages:

- **Stage 1**: May to July; loading rate: 10 tons thickened sludge per four days.
- **Stage 2**: August; loading rate: 15 tons thickened sludge per four days.
- **Stage 3**: September to November; loading rate: 7 tons thickened sludge per four days.

Plant growth

At the beginning of the system startup, three pipes were used for sludge distribution in case of local high loading producing negative impact on plant growth. After a layer of fixed sludge was formed on the surface of the substrata, sludge distribution was completed by one pipe set at one side of the bed. The results proved that the *Phragmites australis* grew healthily after a period of adjustment.

In summer of 2005, kinds of weeds grew together with *Phragmites australis*, but reed growth was superior to the weeds. Growing period was longer for *Phragmites australis* shoots treated with sewage sludge than on natural stands (Hardej & Ozimek 2002). It was also found in this experiment that *Phragmites australis* grew 10–15 days earlier than natural
one in 2006; regrowth of plants in Spring 2006 was greater than 90%. For different plants comparison, a corner of a quarter area was chosen and replanted with *Typha augustifolia*.

Sludge contains plenty of nutrients, which are helpful for plant growing. *Phragmites australis* length in the wild and in the system was measured during growing season from May to July 2006. The plant growth superiority in the system is more obvious with plant growing. The system reeds can keep 20–30 cm superiority during early growing period and 50–100 cm superiority during final growing period in comparison with natural ones.

Compared with the system, the nutrients of natural plant come from soil, while soil nutrients are limited due to shortage of external nutrients supply. When soil nutrients become the factor of limitation for plant growing, abundant nutrients in the system ensure and simulate plant growing.

### RESULTS AND DISCUSSION

**Dried sludge permeation performance**

In the process of sludge ecological stabilization, dewatering process can be ascribed to evapotranspiration, percolation and mineralization (De Maeseneer 1997). Planting of reeds in sludge showed several positive effects such as higher dry weight contents of the residual sludge, enhanced decomposition of the organic matter, better quality of the percolated water (Hofmann 1990). That *Phragmites australis* has a positive impact on percolation may be caused by the change in the colloidal structure of the sludge, in the immediate vicinity of the plant roots humic acid sols are produced from which water is more easily removed, and the movement of the stems in the fresh sludge improves the percolation of water (Hofmann 1990). Penetration of the sludge layers by roots and rhizomes of reed allows for existence of heterotrophic microorganisms and formation of rhizosphere in the shape of characteristic matrix (Zwara & Obarska-Pempkowiak 2000). The rhizomes and root system of *Phragmites australis* penetrate the growing medium and help channel wastewater flow (Begg et al. 2001).

Thus the filtration process of percolated water is complicated. Except for the permeation performance of dried sludge, sludge structure, moisture and organic matter content at different sludge drying time are different, and additionally plant root and stem growing and aging, all of these factors affect the performance of percolate permeation.

Ten groups of data were measured in 2006. **Figure 2** reported permeation coefficient variation of dried sludge with operation time, **Figure 3** reported the permeation coefficients comparison between dried sludge layer and substrata layer.

**Figure 2** demonstrates that the time of percolation across a dried sludge layer does not increase but varies uncertainly with operation time or sludge thickness increasing, such as the shortest time occurred at the last measurement. The permeation coefficients have the similar variation trend. Also the time of permeation is shorter than that of theoretical

Table 1: Characteristics of thickened sludge

<table>
<thead>
<tr>
<th>Characteristics of thickened sludge</th>
<th>TS/g/L</th>
<th>VS/g/L</th>
<th>Moisture/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>5.3–38.82</td>
<td>1.73–11.5</td>
<td>89–99.5</td>
</tr>
<tr>
<td>Average</td>
<td>22.34</td>
<td>7.76</td>
<td>97</td>
</tr>
<tr>
<td>Sludge loading (avg.)</td>
<td>0.166–1.213(0.691) kg TS/m²·d</td>
<td>0.054–0.548(0.24) kg VS/m²·d</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60.6–442.7(252.2) kg TS/m²·yr</td>
<td>19.7–200(87.6) kg VS/m²·yr</td>
<td></td>
</tr>
<tr>
<td>VS/TS</td>
<td>0.347</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2](https://iwaponline.com/wst/article-pdf/58/10/1911/435895/1911.pdf)
analysis value, i.e. dried sludge layer has higher permeation coefficients. Thus it is suggested that the percolate did not filtrate downwards evenly, but part of percolate filtrates downwards along stems, roots and cracks existing in dried sludge which have lower flow resistance, the other percolate will be lost by dried sludge intake and evapotranspiration.

Figure 3 compares the permeation coefficients of dried sludge layer and substrata layer, which are in the range of 0.15–1.5 m/h and 0.9–3.6 m/h, individually. Obviously, the substrate layer has greater permeation coefficient due to its larger opening rate even if parts of the holes were filled by treated sludge and biofilm after thirteen months operation.

**Dried sludge thickness variation**

Dried sludge thickness variation is a complicated process, which is affected by the following factors: sludge moisture, the degree of organic matter degradation, dried sludge hole density, plant root growth and aging. These factors vary continuously with the system operation, thus it is difficult to build dried sludge thickness variation model if considering all impact factors, while the previous researches only presented sludge increase trend over long time period (Lienard et al. 1995). Dried sludge thickness variation with time in 2006 is reported in Figure 4 (sludge loadings are not be considered).

In the year of 2005, the system had about 10 cm of dried sludge thickness. Based on the form of curve in Figure 4, the relationship of dried sludge thickness and operation time is in accord with quadratic equation as follows:

\[ y = -0.0005x^2 + 0.2605x + 9.1532 \quad R^2 = 0.9788 \]

This equation has better relationship with the correlation coefficient \( R^2 \) of 0.9788, which can indicate dried sludge thickness variation with operation time under experimental conditions.

It is noted that dried sludge thickness does not increase with sludge input before the 24th of system operation in 2006. The reasons are suggested that, in the freezing period from December 2005 to March 2006, the system stopped loading; while after April 2006, frozen sludge began to thaw, the sludge went through the process of freezing and thawing, and dewatered efficiently. In addition, cracks occurring on the surface of dried sludge extended downwards. After the system began to operate in 2006, due to sludge dewatering and the cracks, the hole in dried sludge provided large position for new sludge storage, resulting in inconspicuous dried sludge thickness variation.

For investigating dried sludge thickness variation under different sludge loadings, a dried sludge thickness variation model was built based on the sludge loadings.

Dried sludge thickness variation model under different sludge loadings was built through linear regression as follows:

- **Sludge loading 7t/4d**: \( y = 0.1162x + 19.488 \quad R^2 = 0.964 \)
- **Sludge loading 10t/4d**: \( y = 0.2588x + 6.8182 \quad R^2 = 0.95 \)
- **Sludge loading 15t/4d**: \( y = 0.2981x + 4.9154 \quad R^2 = 0.95 \)

Based on above models, regression coefficients are greater than 0.93; this demonstrates that linear relationship can indicate dried sludge thickness variation with time even though many factors have the effect on sludge thickness. It is noted that the curve slopes are 0.1162 (7t/4d), 0.2588 (10t/4d), and 0.2981 (15t/4d).
(10t/4d), 0.2981 (15t/4d) under three sludge loadings, i.e., the rate of dried sludge thickness growth increases with sludge loadings increasing.

Dried sludge structure variation

The variation of dried sludge physical–chemical characteristics has strong relationship with its permeation performance. Based on the research of Barbieri et al. (2003), the dewatering level of dried sludge had an increasing trend during the length of the whole experimentation and dewatering activity did not depend on the initial amount of TS. This experiment got the similar result, moisture and organic matter content in dried sludge decrease from the surface to the bottom of dried sludge layer.

For investigating sludge structure variation, samplings were taken at four different dried sludge layer: the surface, a depth of 5 cm, a depth of 20 cm and the bottom, and analyzed through scanning electron microscope (SEM) (see Figure 5).

From Figure 5 (a)–(d), it is found that fixed holes in dried sludge are formed gradually from the surface to the bottom. It is suggested that these holes are formed through sludge dewatering, organic matter degradation, gas discharge by nitrification/denitrification and humic aged roots; these processes are enhanced with increasing sludge dried time in the system.

Plant component and plant biomass

At the end of the growing season in 2006, samples of Phragmites australis and Typha augustifolia were taken from the wild and the system, and moisture, coarse protein, coarse fat and coarse fiber contents in roots, and stems and leaf were analyzed, the analytical results are listed in Table 2.

It is worth to note that not only roots but also stems and leaf in the system, their coarse protein, coarse fat and coarse fiber contents are higher than that of the wild. Especially coarse protein content of Phragmites australis roots in the system is twice as high as that of the wild, coarse fiber content of roots, coarse fat content of stems and leaf in the

<table>
<thead>
<tr>
<th>Item</th>
<th>Root in wild</th>
<th>Root in system</th>
<th>Stem and leaf in wild</th>
<th>Stem and leaf in system</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Phragmites australis</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture(%)</td>
<td>70.56</td>
<td>71.12</td>
<td>58.21</td>
<td>58.29</td>
</tr>
<tr>
<td>Coarse protein(%)</td>
<td>3.29</td>
<td>7.38</td>
<td>6.96</td>
<td>7.77</td>
</tr>
<tr>
<td>Coarse fat(%)</td>
<td>1.05</td>
<td>1.14</td>
<td>1.37</td>
<td>2.21</td>
</tr>
<tr>
<td>Coarse fiber(%)</td>
<td>26.00</td>
<td>33.64</td>
<td>33.63</td>
<td>35.77</td>
</tr>
<tr>
<td><em>Typha augustifolia</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture(%)</td>
<td>72.50</td>
<td>72.10</td>
<td>77.84</td>
<td>75.83</td>
</tr>
<tr>
<td>Coarse protein(%)</td>
<td>3.47</td>
<td>9.34</td>
<td>3.52</td>
<td>5.19</td>
</tr>
<tr>
<td>Coarse fat(%)</td>
<td>1.00</td>
<td>1.18</td>
<td>1.75</td>
<td>1.92</td>
</tr>
<tr>
<td>Coarse fiber(%)</td>
<td>14.63</td>
<td>17.38</td>
<td>45.84</td>
<td>47.45</td>
</tr>
</tbody>
</table>
system is obviously higher than that of the wild; coarse protein content of *Typha augustifolia* in the system is higher than that of nature, while coarse fat and coarse fiber contents have no significant difference.

Choosing one square metre both in the system and the wild as comparison, *Phragmites australis* were harvested in November 2006 and weighed. Average single weight was 18.52 g in the system and 11.13 g in the wild. Based on these data, we can conclude that the biomass in the system is higher than that of the wild, and parts of nutrients in the sludge are transformed into plant components, dried sludge in the system can stimulate plant growth, from the point of source utilization, sludge completes source transformation at the same time of sludge being stabilized.

**CONCLUSIONS**

Ecological stabilization for thickened sludge from the CAST process with relatively lower VS/TG of average 34.7% has performed well in the Northeast of China. Dried sludge layer has higher permeation coefficient; the percolate filtrates preferentially downwards along the path of lower flow resistance such as stems, roots and cracks.

The relationship of dried sludge thickness and operation time is in accord with quadratic equation under fluctuating sludge loadings. Linear regression equation can indicate dried sludge thickness variation under fixed sludge loading.

Coarse protein, coarse fat and coarse fiber contents of *Phragmites australis* and *Typha augustifolia* harvested in the system flooded with thickened sludge were higher than that of the wild.

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