Theoretical and Experimental Verification of Rheological Characteristics of High Viscosity Municipal Sludge

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Abstract. After upgrading the wastewater treatment standard, the effluent quality reached the first class A standard by strengthening the process optimization of biological dephosphorization and denitrification. Taking the sludge treatment project of Shanghai Bamboo Garden as an example, the sludge composition from the fourth plant is compared with the weighted value of the sludge before the upgrading of the standard, and the sludge element content is obviously increased and the sludge viscosity is increased. By kinexus lab+ series of rotary rheometer to test the viscosity of the sample sludge, it is concluded that the viscosity zone of the sample sludge is between 45% and 55% solid content. The rheological test of sludge characterization-viscosity-thixotropy and stacking test standard shows that the viscous zone of sludge is about 40% or more. Herschel-Bulkley model is basically suitable to describe the rheology of sludge in this sample when the solid content is more than 44%. To avoid the sludge viscous zone is the key to design the sludge transport system and the subsequent drying incineration system process parameters in the sludge treatment project of Shanghai Bamboo Garden.

1. Effect of wastewater treatment and upgrading on sludge characteristics

After upgrading the wastewater treatment standard, by strengthening the process optimization of biological dephosphorization and denitrification, the effluent quality reached the first class A standard, which made the sludge more complex. There are many factors affecting denitrification ability, including mud age, carbon source, anoxic tank HRT, dissolved oxygen concentration, reflux ratio, temperature, PH and so on.

1.1 Present situation and technical standard of upgrading wastewater treatment

The A/O and A of nitrogen and phosphorus removal biological treatment for municipal wastewater are mainly included. O series processes, oxidation ditch series processes and SBR series processes, while A/O and A processes are the most widely used ones. A2O process is to add anaerobic and anoxic tanks in front of aerobic aeration tanks by ordinary activated sludge process, so that phosphorus accumulating bacteria can release phosphorus under anaerobic and sufficient carbon sources, and then absorb phosphorus in excess under oxygen-enriched conditions, and transfer phosphorus to sludge to achieve the purpose of phosphorus removal.

1.2 Comparison of sludge composition before and after upgrading

Taking the sludge treatment project of bamboo garden in Shanghai as an example, after upgrading the standard of sewage treatment, the sludge composition from the fourth plant is compared with the
weighted value of the sludge from the first four plants, as shown in Table 1:

**Table 1.** Comparison of sludge composition before and after bid raising (data from Shanghai Bamboo Garden sludge treatment Project request for proposal)

| Project                | Prior to proposal | Proposal submitted |
|------------------------|-------------------|--------------------|
|                        | Weight 1 factory | Second Factory     | Quyang          | Si Tong         |
| Water content (%)      | 80                | 77.96              | 85.27           | 86.42           | 83.15           |
| High calorific value (MJ/kg) | 12.19           | 14.68              | 13.59           | 16.90           | 16.49           |
| Low calorific value (MJ/kg) | 11.30           | 13.66              | 12.64           | 15.76           | 15.32           |
| (%) sand content       | 29.8              | 29.35              | 27.92           | 17.47           | 21.70           |
| C(%)                   | 27.17             | 31.58              | 29.99           | 36.84           | 36.40           |
| H(%)                   | 4.19              | 4.98               | 4.61            | 5.49            | 5.66            |
| O(%)                   | 18.83             | 20.81              | 20.53           | 24.59           | 21.87           |
| N(%)                   | 2.02              | 5.70               | 5.90            | 7.11            | 6.58            |
| S(%)                   | 0.91              | 0.99               | 0.49            | 0.60            | 0.41            |
| P(%)                   | 0.02              | 1.30               | 1.95            | 1.32            | 1.24            |
| Cl(%)                  | 0.64              | 0.049              | 0.051           | 0.059           | 0.041           |
| Ash                    | 46.79             | 33.24              | 36.12           | 42.10           | 37.8            |

It can be seen that the sludge composition is more complex and the element content is obviously increased after the upgrading of the sewage treatment plant, which will inevitably lead to the change of sludge viscosity.

2. **Theoretical Study on Rheological Characteristics of Sludge**

Sludge is a non-Newtonian fluid and its rheological properties are affected by many factors, such as sludge composition, moisture content, organic matter content and so on\(^{[9]}\). In general, the more complex the sludge composition, the greater the sludge viscosity. As a high viscosity non-Newtonian fluid, sludge with different moisture content has many interactions, such as yield stress, shear force, thixotropy, viscoelasticity, wall slip and tear\(^{[10]}\).

The relationship between shear stress and shear strain rate is a straight line through the origin, and its viscosity changes only with the change of temperature and pressure, and has nothing to do with shear strain rate\(^{[11]}\). The non-Newtonian fluid is plastic, pseudo-plastic and expansive\(^{[12]}\). As shown in the diagram. For pseudoplastic and expansive fluids, the nonlinear characteristics are usually described by exponential relation approximation, that is, the sum is constant, the shear rate, the Newtonian fluid, and the dynamic viscosity.  

\[
\tau = \dot{\gamma}^n + \dot{\gamma} n = 1 t
\]

Several typical rheological models of sludge are as follows:

1. **Power law model:** \(\tau = \dot{\gamma}^n\)  
2. **Bingham models:** Bingham models of viscosity enhancement:
(3) Herschel-Bulkley model; viscous Herschel-Bulkley model; Thixotropy Herschel-Bulkley model:
\[ \dot{\tau} = \tau_\eta + \eta \dot{\gamma} \]

\[ \dot{\lambda} = \dot{\gamma} \]

(4) Four-parameter model:
\[ \dot{\tau} = \tau_\eta + \eta \dot{\gamma} + \lambda \dot{\gamma}^n \]

(5) Casson models:
\[ \dot{\gamma} = \sqrt{\tau_\eta} - \sqrt{\tau_\eta} / \eta_c \]

(6) Orry model:
\[ \dot{\gamma} = \alpha \dot{\gamma}^3 + c \gamma \]

(7) Ree-Eying models:
\[ \tau = X_1 \frac{\beta_1}{\alpha_1} \dot{\gamma} + X_2 \frac{\beta_2}{\alpha_2} ar sinh \beta_2 \dot{\gamma} \]

Garakani and other studies show that the Herschel-Bulkley model is suitable for describing the rheological properties of high concentration activated sludge, while the Bingham model is suitable for characterizing low concentration sludge.

3. Experimental verification of 3 sludge rheological properties

3.1 Sludge viscosity test

Taking the sludge project of Shanghai bamboo garden as an example, the sludge samples of the first plant of bamboo garden were tested for viscosity. The solid content was 25%, 35%, 45%, 55%, and 60% respectively. The curve of viscosity with shear rate is shown in figure 3.
from the data curve we can read that when this sludge sample, when the solid content of the sludge is 25%, 35% and 60%, it is approximately linear and decreases with the increasing viscosity of the shear rate. If the solid content is 45%, when the shear rate reaches 10 s⁻¹, the viscosity decreases suddenly. When the solid content is 55, when the shear rate reaches 1 s⁻¹, the viscosity decreases greatly, and when the shear rate reaches 13 s⁻¹, the viscosity decreases to the initial level. The relationship between viscosity and shear rate is greatly affected by the solid content of sludge.

3.2 Testing of sludge rheology

Sludge samples were taken from sludge detection, and the sludge sample size was more than 20 kg each time. For sludge characterization-viscosity-thixotropy and stacking (CEN/TR 15463: 2007), the experimental device diagram of sludge rheology test is shown in figure 4.

Taking the sludge with a solid content of 35% as an example, when the working pressure is 2 kg/cm², the interface of the experimental process is shown in figure 5. It can be found that in 1513 s, the sludge outflow quality and time basically show a linear trend with the extension of time.

In the experiment, the rheology of sludge with different solid content is compared. We test the relationship between sludge outflow quality and time with different solid content, and form a contrast image, as shown in figure 6-8.
Combined with the above, the viscosity of sludge with different solid content is calculated as follows:

Table 2. Viscosity values of sludge with different solid content

| Number | (%) of sludge solid content | Viscosity (kPa’S) |
|--------|-----------------------------|-------------------|
| 1      | 22                          | 1.1-30            |
| 2      | 34                          | 16-342            |
| 3      | 44                          | 4215-18658        |
| 4      | 50                          | 5422-17894        |

Therefore, we can conclude that in general, the viscosity of 44% solid sludge is more than 50 times that of 34% solid sludge. Because of the inhomogeneity of sludge, the viscosity difference sometimes exceeds 100 times. When the solid content of sludge samples exceeds 40, the viscosity of sludge samples will increase significantly. It can also be seen that the viscous zone of the sample sludge is about 40% or more. Herschel-Bulkley model is suitable to describe the rheology of sludge in this sample when the solid content is more than 44%.
4. Conclusions
(1) After upgrading the standard of sewage treatment plant, the content of elements increased obviously, which resulted in the change of sludge viscosity.
(2) The sludge viscosity test results show that the sludge viscosity zone of the sample is between 45% and 55% respectively. Through the test of sludge rheology, it is known that the viscous zone of sludge is about 40% or more.
(3) The Herschel-Bulkley model is basically suitable for describing the rheology of sludge in this sample when the solid content is above 44%.

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