Sewage Sludge Treatment and Disposal

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Introduction of Sewage Sludge

1. Waste water treatment process

2. Sludge dewatering method

3. Characteristics of sludge

4. Sludge treatment and disposal methods

5. Research and development in ZJU
Waste Water

- Industrial wastewater: from industrial processes
- Sewage: from residences and institutions
- Surface runoff: rain

Industrial wastewater

Sewage
Waste Water Treatment Plant (WWTP) is the plant to remove pollutants from wastewater. It includes physical, chemical, and biological processes to remove these pollutants and produce clean water.
## Treatment Methods

<table>
<thead>
<tr>
<th>Physical Processes</th>
<th>Chemical Processes</th>
<th>Biological Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screening</td>
<td>Precipitation</td>
<td>Aerobic</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>Chlorination</td>
<td>Anaerobic</td>
</tr>
<tr>
<td>Filtration</td>
<td>Disinfection</td>
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</tr>
</tbody>
</table>
Sewage treatment generally involves **three stages**: primary treatment, secondary treatment and tertiary treatment.
Primary treatment consists of temporarily holding the sewage in a quiescent basin where heavy solids can settle to the bottom while oil, grease and lighter solids float to the surface.
**Secondary treatment** removes dissolved and suspended biological matter. Secondary treatment is typically performed by indigenous, water-borne micro-organisms.

- Removes harmful effect of biodegradable organic matter
- Usually micro-organisms and oxygen are mixed with the filtered waste (from primary treatment)
- Provide BOD removal beyond what is achieved in primary treatment
- Basic approach is to use aerobic biological degradation:

\[
\text{Organic carbon} + \text{O}_2 \rightarrow \text{CO}_2
\]
**Treatment Process**

**Secondary treatment** should **create a very rich environment for growth of a diverse microbial community.**

- **High density of micro-organisms**
  -- keep organisms in system
- **Good contact between organisms and wastes**
  -- provide mixing
- **Provide high levels of oxygen**
  -- aeration
- **Favorable temperature, pH**
  -- design and operation
- **No toxic chemicals present**
  -- control industrial inputs
Activated Sludge
◆ Process in which a mixture of wastewater and microorganisms
◆ Leads to oxidation of dissolved organics
◆ Separate sludge from wastewater after oxidation,
Tertiary treatment is sometimes defined as anything more than primary and secondary treatment in order to allow ejection into a highly sensitive or fragile ecosystem.

- Treated water is sometimes disinfected chemically or physically.
- If it is sufficiently clean, it can also be used for groundwater recharge or agricultural purposes.
Simplified process flow diagram for a typical large-scale treatment plant
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Water content of sludge may be reduced by centrifugation, filtration, and/or evaporation to reduce moisture content. Centrifugation may be a preliminary step to reduce sludge volume for subsequent filtration or evaporation. Filtration may occur through underdrains in a sand drying bed or as a separate mechanical process in a belt filter press.
Sludge Dewatering Method

Sludge dewatering difficulties

The difficulties in sludge dewatering are associated with the high organic content and colloidal materials in sludge solids. Indeed sludge is a colloidal system in which small solid particles form a stable suspension in water which is very difficult to be separated from the water phase. It is expected that dewater ability of sludge is related to the particle size and particle size distribution of the solids within it, chemical composition and compressibility of solids and other factors such as the length of fibers presented in the sludge. It is generally accepted that the presence of large fraction of long fibers in sludge makes it easier to be dewatered.
In order to improve sludge dewaterability, proper sludge conditioning is a key point. Conditioning is to add some chemical materials to change sludge properties to achieve effective dewatering.
Sludge Dewatering Method

Chemical conditioning sludge dewatering technology

By adding the flocculants, the sludge colloid is stabilized by compressing the double electric layer, charge neutralization, adsorption bridging and net trapping, then the solid-liquid phase can separation. The sludge water content is further reduced by gravity sedimentation.

The flocculation model of flocculants
The flocculants can be classified into three categories including chemical flocculants, natural bio-flocculants and grafted flocculants.

Classification of flocculants

- **Chemical Coagulants / Flocculants**
  - Coagulants: Inorganic metal salts
  - Flocculants: Synthetic organic polymers

- **Natural Bio-flocculants**
  - Chitosan
  - Cellulose
  - Gums and mucilage
  - Sodium alginate
  - Tannin

- **Grafted Flocculants / Graft Copolymers**
  - Synthetic polymers: polyacrylamide, poly(2-methacryloyloxyethyl) trimethyl ammonium chloride
  - Natural polymers: chitosan, cellulose, gums and mucilage, oatmeal, sodium alginate, starch
Chemical conditioning sludge dewatering technology

- **Inorganic flocculants** (salts of multivalent metals) are being commonly used due to its low cost and ease of use. However, their applications constrained with low flocculating efficiency and the presence of residue metal concentration in the treated water.

- **Organic polymeric flocculants** are widely used nowadays due to its remarkable ability to flocculate efficiently with low dosage. However, its application is associated with lack of biodegradability and dispersion of monomers residue in water that may represent a health hazard.
Due to the density difference between solid and liquid, the settling velocity of solid particles is accelerated by centrifugal force to achieve solid-liquid separation.
**Belt filter**

Under the influence of negative pressure (0.04-0.07MPa), the liquid in the suspension is pumped through the filter medium (filter cloth), while the solid particles are trapped by the medium, then solid-liquid separation can be achieved.
Sludge Dewatering Method

Pressure filtering

It consists of many plates and frames assembled alternately with the supports of a pair of rails. For each of the individual separating chambers, there is one hollow filter frame separated from two filter plates by filter cloths. The introduced slurry flows through a port in each individual frame, and the filter cakes are accumulated in each hollow frame.
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Water Content

Water in sludge

- Free water
- Interstitial water
- Surface water
- Bound water

\[ W = \frac{M_0 - M_1}{M_0} \times 100\% \]

where
- \( W \) is the water content of sludge
- \( M_0 \) is the mass of the sludge sample
- \( M_1 \) is the mass of sludge that had been oven-dried at 105°C until the residual mass was constant
Water Content

Relation of water content (W) and volume (V):

\[ \frac{V_1}{V_2} = \frac{1 - W_2}{1 - W_1} \]

Question:
Water content of sludge decreases from 90% to 80%, calculate the change of volume.

Solution:

\[ \frac{V_1}{V_2} = \frac{1 - W_2}{1 - W_1} = \frac{1 - 0.8}{1 - 0.9} = 2 \]
Dewaterability

SRF (specific resistance to filtration)

\[ r = \frac{2PA^2t}{\mu cV^2} \]

where:
- \( r \) is the specific resistance to filtration (m/kg);
- \( P \) is the vacuum (Pa);
- \( A \) is the filtration area (m\(^2\));
- \( t \) is the time (s);
- \( \mu \) is the filtrate viscosity (Pa·s);
- \( c \) is the suspended solids concentration (kg/m\(^3\));
- \( V \) is the volume of filtrate (m\(^3\))
Sludge is placed in the sludge well and the water moves radically outwards from the sludge. The time taken for the liquid moves between two pre-set points on the filter paper is recorded and defined as CST.
Biochemical Properties

**TS (total solid)**

\[ TS = \frac{M_1}{M_0} \times 100\% \]

**VS (volatile solid)**

\[ VS = \frac{M_1 - M_2}{M_0} \times 100\% \]

where

- \( M_0 \) is the mass of the sludge sample;
- \( M_1 \) is the mass of sludge that had been oven-dried at 105°C until the residual mass was constant;
- \( M_2 \) is the mass of sludge that had been oven-dried at 550°C until the residual mass was constant;
COD (chemical oxygen demand) is a measurement of the oxygen required to oxidize soluble and particulate organic matter in a sample.

How to measure COD?

Step 1: Sample + excess oxidant (i.e. potassium dichromate)
Step 2: Digestion at 150°C for 2 hours
Step 3: Read the samples by spectrophotometer
BOD (biological oxygen demand) is the amount of dissolved oxygen needed by aerobic biological organisms to break down organic material present in a given water sample at a certain temperature over a specific time period.

Most common - BOD<sub>5</sub>: at 20°C for 5 days

How to measure BOD?

Step 1: pH setting of sample (6~8)
Step 2: Sample dilution
Step 3: Sample incubation
Step 4: Measurement of DO (dissolved oxygen)
Step 5: Calculation of BOD

\[
\text{BOD} = \frac{\text{DO}_0 - \text{DO}_1}{P}
\]

Where
- \(\text{DO}_0\) is DO before incubation
- \(\text{DO}_1\) is DO after incubation
- \(P\) is the dilution factor
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Sludge Drying

- Sludge dryer
  - Convection dryer
    - Belt
    - Flash
    - Fluid bed
    - Rotary
  - Solar dryer
  - Conduction dryer
    - Disc
    - Paddle
    - Thin film
Sludge Drying

Belt dryer

1. pivoting conveyor belt
2. substrate
3. deflection unit
4. drying plates
5. warm air
6. drive unit
7. throw-off vat
Sludge Drying

Fluid bed dryer
Sludge Drying

Rotary dryer
Sludge Drying

Disc dryer

Thermal oil return  Mix of wet & dry sludge  Vapours  Hot thermal oil  Dry sludge
Sludge Drying

Paddle dryer
Sludge Drying

Thin film dryer

- Motor
- Vapor separator
- Vapor outlet
- Stationary plates
- Agitator
- Vent
- Steam jacket
- Condensate
- Concentrate

![Thin film dryer diagram](image1.png)

![Industrial thin film dryer](image2.png)
Sludge Drying

Solar dryer
<table>
<thead>
<tr>
<th>Dryer types</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective dryer</td>
<td>• Design allowing easy manipulation&lt;br&gt;• Dried product used in agriculture</td>
<td>• Relatively long drying time&lt;br&gt;• Bad odours&lt;br&gt;• Gaseous emissions</td>
</tr>
<tr>
<td>Conduction dryer</td>
<td>• No pollution of the heat carrying medium&lt;br&gt;• Steam and odor confinement&lt;br&gt;• VOC concentration is low&lt;br&gt;• Reduction of fire and explosion risks&lt;br&gt;• Dried product used in industrial applications</td>
<td>• Relatively long drying time&lt;br&gt;• Sticky phase alters dryer performances</td>
</tr>
<tr>
<td>Solar dryer</td>
<td>• Use of free solar energy&lt;br&gt;• Pathogen free sludge&lt;br&gt;• Dried product used in agriculture&lt;br&gt;• During the same operation, important quantities are dried</td>
<td>• Depends on climatic conditions&lt;br&gt;• Relatively long drying time&lt;br&gt;• High surfaces are needed</td>
</tr>
</tbody>
</table>

Anaerobic digestion is a collection of processes by which microorganisms break down biodegradable material in the absence of oxygen.

4 Stages:
- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

Sludge digestion towers in Shijiazhuang, China
Anaerobic Digestion

- Suspended organic matters
- Soluble organics
- Volatile fatty acids (VFA)
- $\text{H}_2 + \text{CO}_2$
- Acetate
- $\text{CH}_4 + \text{CO}_2$

Stage 1: Hydrolysis
Stage 2: Acidogenesis
Stage 3: Acetogenesis
Stage 4: Methanogenesis
Recommended conditions:

- **pH:** 7-7.5
- **Temperature:**
  - Mesophilic digestion (30~38°C)
  - Thermophilic digestion (49~57°C)
Products from anaerobic digestion

**Biogas:**

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Pie chart of Raw Biogas
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- **CO₂:** 39-29%
- **CH₄:** 60-70%

**Digestate:**

The material remaining after the anaerobic digestion of a biodegradable feedstock.

**Uses:** solid conditioner, fertilizer
Anaerobic Digestion

THE ANAEROBIC DIGESTION PROCESS

- Grinding Mixing Tank
- Pre-Heat Tank
- Anaerobic Digester
- Biogas
- Biogas Condensing/Storage
- Biogas Purification Module
- Combined Heat & Power Generator
- Electricity Grid
- Electricity to Power Facility
- Facility Heater
- Captured Heat From CHP
- Liquid Digestate Re-Entered into System
- To Pre-Heat Tank
- To AD Unit
- Digested
- Solids Separation Tank
- Solid Organic Compost
- Facility Heat
- Liquid Organic Fertilizer
- Tractor
## Anaerobic Digestion

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gas production;</td>
<td>1. Long processing time;</td>
</tr>
<tr>
<td>2. Low risk of air and water</td>
<td>2. Environmental Sensitivities</td>
</tr>
<tr>
<td>pollution;</td>
<td></td>
</tr>
<tr>
<td>3. Reduction of sludge volume;</td>
<td></td>
</tr>
<tr>
<td>4. Relatively low capital costs;</td>
<td></td>
</tr>
<tr>
<td>5. Economic benefits</td>
<td></td>
</tr>
</tbody>
</table>
Composting is nature's process of recycling decomposed organic materials into a rich soil. Composting is a key ingredient in organic farming.

Fundamentals

- **Carbon** — for energy; the microbial oxidation of carbon produces the heat, if included at suggested levels.
- **Nitrogen** — to grow and reproduce more organisms to oxidize the carbon.
- **Oxygen** — for oxidizing the carbon, the decomposition process.
- **Water** — in the right amounts to maintain activity without causing anaerobic conditions.
Composting

Stages
• In the beginning, mesophilic phase, in which the decomposition is carried out under moderate temperatures by mesophilic microorganisms.
• As the temperature rises, a second, thermophilic phase starts, in which the decomposition is carried out by various thermophilic bacteria under high temperatures.
• As the supply of high-energy compounds dwindles, the temperature starts to decrease, and the mesophiles once again predominate in the maturation phase.

Recommended conditions
• Water content : 50%~60%
• pH : 5~8
• C/N : 25~30

Uses of compost
• Agriculture
• Horticulture
• Erosion control
**Composting**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. A reduction in the volume;</td>
<td>1. Long processing time;</td>
</tr>
<tr>
<td>2. A facilitation of storage and use;</td>
<td>2. Aeration consumes energy;</td>
</tr>
<tr>
<td>3. Control of compost material</td>
<td>3. A need for an outlet market for the compost end product</td>
</tr>
<tr>
<td>specifications;</td>
<td></td>
</tr>
<tr>
<td>4. Control of nutrient content;</td>
<td></td>
</tr>
<tr>
<td>5. Product hygiene control before</td>
<td></td>
</tr>
<tr>
<td>agricultural application;</td>
<td></td>
</tr>
</tbody>
</table>
Incineration is a sludge disposal option that involves drying and burning. The process reduces sludge to a mass of ash. Drying occurs at a temperature of approximately 350°C, and burning is sustained at 700~800 °C.
Incineration

Rotary kiln incinerator
Incineration

Multiple-Hearth incinerator
Incineration

Fluid bed incinerator
### Incineration

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Reduction of the sludge volume;</td>
<td>1. High capital and operating costs;;</td>
</tr>
<tr>
<td>2. Complete destruction of pathogens;</td>
<td>2. Reduces the potential beneficial use of biosolids;</td>
</tr>
<tr>
<td>3. Recycling of sludge treatment subproducts such as ashes and inert material;</td>
<td>3. The residuals (ash) may be classified as hazardous waste;</td>
</tr>
<tr>
<td>4. Low sensitivity to sludge composition;</td>
<td>4. Discharges to atmosphere require extensive treatment to assure protection of the environment.</td>
</tr>
</tbody>
</table>
Sludge Landfilling is disposal of sludge by burial, it’s the oldest form of sludge treatment. The cost of landfilling is much less than other treatments.
Types of landfilling

• **Exclusive sanitary landfill**
  
  Especially designed and constructed to receive sewage sludge, incorporating special features to cope with specific sludge properties and to comply with environmental constraints.

• **Co-disposal with other waste**

  Sludge is disposed of in a landfill with municipal solid wastes. Mixing of sludge with other wastes tends to accelerate the biodegradation process as a function of the nitrogen content and the sludge inoculation potential. The inconvenience of this alternative is the reduction of landfill lifetime if the amount of sludge is significant.
## Landfilling

### Main environmental aspects for selecting landfills sites

<table>
<thead>
<tr>
<th>Aspect to be considered</th>
<th>Characteristics to be evaluated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface and groundwater</td>
<td>• Site geology and hydrology&lt;br&gt;• Localisation of surface water bodies&lt;br&gt;• Site location within the watershed and local use of water resources&lt;br&gt;• Local climate</td>
</tr>
<tr>
<td>Air</td>
<td>• Local climate&lt;br&gt;• Direction of prevailing winds&lt;br&gt;• Distance and transition areas to housing developments</td>
</tr>
<tr>
<td>Soli</td>
<td>• Soils characteristics&lt;br&gt;• Local flora and fauna&lt;br&gt;• Site geology and hydrology</td>
</tr>
<tr>
<td>Anthropic environment</td>
<td>• Landscape changes&lt;br&gt;• Aesthetic changes&lt;br&gt;• Distance from housing developments&lt;br&gt;• Direction of prevailing winds&lt;br&gt;• Change in land value&lt;br&gt;• Local legislation</td>
</tr>
</tbody>
</table>
Landfilling

Risks

- Heavy metals
- Organic chemicals
- Pathogens
- Odours
1. Waste water treatment process
2. Sludge dewatering method
3. Characteristics of sludge
4. Sludge treatment and disposal methods

5. Research and development in ZJU
Production of sludge

- In China, the total amount of the treated waste water is up to 0.13 billion m³/day, the quantity of the sewage sludge is up to 30 million tons/year (80% moisture)

  → Beijing: 1600 tons/day
  → Shanghai: 3500 tons/day
  → Guangzhou: 2000 tons/day
  → Shenzhen: 2600 tons/day

A serious environmental problem as MSW

- The production of the industrial sludge is as many as the sewage sludge

  → Papermaking
  → Printing and dyeing
  → Textile
Challenge to environment

- Because the safe disposal of the sludge was ignored in the past, the traditional way is to pile or landfill simply, which brought big challenge to environment.

- Sludge management became an ever-increasing problem due to environmental pollution and energy consumption in China.
More than 80% of the sludge has not yet been disposed safely

The Waste Water Treatment Plant (WWTP) always is mixed by the industrial waste water, incineration will become an increasing disposal method for the sludge treatment in the coming years.
The technique of drying and incineration of sludge is encouraged because it can turn sludge into energy.

Sludge incineration plant and MSW incineration plant are encouraged to be built together.

Sludge is encouraged to be co-combustion in coal-fired power plants boiler, cement kiln as a kind of low-quality fuel.
# Heavy metals

- Heavy metals is the first thing that we must consider for sludge
- Chinese sludge always exceed the national limitation for agriculture utilization

<table>
<thead>
<tr>
<th>Sludge</th>
<th>Cr</th>
<th>Cd</th>
<th>Hg</th>
<th>Pb</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>Fe</th>
<th>K</th>
<th>Na</th>
<th>As</th>
<th>Se</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant 1</td>
<td>60.859</td>
<td>5.875</td>
<td>101.311</td>
<td>53.616</td>
<td>66.497</td>
<td>853.410</td>
<td>465.116</td>
<td>13280.67</td>
<td>10743.73</td>
<td>2346.41</td>
<td>18.709</td>
<td>25.612</td>
<td>13.84</td>
</tr>
<tr>
<td>Plant 2</td>
<td>33.809</td>
<td>1.711</td>
<td>120.536</td>
<td>27.140</td>
<td>24.393</td>
<td>914.216</td>
<td>9908.217</td>
<td>5092.863</td>
<td>12781.6</td>
<td>11.172</td>
<td>31.847</td>
<td>11.02</td>
<td></td>
</tr>
<tr>
<td>Plant 3</td>
<td>30.315</td>
<td>2.590</td>
<td>112.465</td>
<td>62.266</td>
<td>16.342</td>
<td>520.396</td>
<td>14215.36</td>
<td>10267.01</td>
<td>2390.93</td>
<td>13.631</td>
<td>28.627</td>
<td>15.32</td>
<td></td>
</tr>
<tr>
<td>Plant 4</td>
<td>1843.79</td>
<td>10.825</td>
<td>149.442</td>
<td>68.130</td>
<td>626.432</td>
<td>681.848</td>
<td>3854.25</td>
<td>22402.59</td>
<td>5234.087</td>
<td>10994.9</td>
<td>11.335</td>
<td>40.678</td>
<td>33.10</td>
</tr>
<tr>
<td>Plant 5</td>
<td>104.088</td>
<td>2.954</td>
<td>75.611</td>
<td>52.999</td>
<td>156.558</td>
<td>424.443</td>
<td>1246.24</td>
<td>13870.22</td>
<td>4595.171</td>
<td>9452.77</td>
<td>6.051</td>
<td>40.709</td>
<td>13.24</td>
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<tr>
<td>National limitation for agriculture utilization</td>
<td>600</td>
<td>5</td>
<td>5</td>
<td>300</td>
<td>100</td>
<td>250</td>
<td>500</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

| Dry season | Plant 1 |  |  |  |  |  |  |  |  |  |  |  |  |
|            | Plant 2 |  |  |  |  |  |  |  |  |  |  |  |  |
| Rain season | Plant 3 |  |  |  |  |  |  |  |  |  |  |  |  |
| Rain season | Plant 4 |  |  |  |  |  |  |  |  |  |  |  |  |
| Rain season | Plant 5 |  |  |  |  |  |  |  |  |  |  |  |  |

Plant 1~Plant 5 are located in Guangdong Province, Unit: mg/kg Dry base
Moisture distribution in sludge

Why the moisture content still has 80% after mechanical dewatering?

- **Free water**
- **Interstitial water**
- **Surface water**
- **Bound water**

Thermal drying to remove

Thermal drying to remove
# Heat values

<table>
<thead>
<tr>
<th>Sludge sources</th>
<th>(C_d) (%)</th>
<th>(H_d) (%)</th>
<th>(N_d) (%)</th>
<th>(S_{t,d}) (%)</th>
<th>(O_d) (%)</th>
<th>(A_d) (%)</th>
<th>(V_d) (%)</th>
<th>(Q_{b,d}) (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shangyu</td>
<td>17.76</td>
<td>2.74</td>
<td>2.18</td>
<td>3.35</td>
<td>8.74</td>
<td>65.05</td>
<td>34.56</td>
<td>7035.16</td>
</tr>
<tr>
<td>Shandong</td>
<td>22.24</td>
<td>3.70</td>
<td>1.19</td>
<td>1.83</td>
<td>19.11</td>
<td>51.93</td>
<td>42.03</td>
<td>9883.10</td>
</tr>
<tr>
<td>Linqi</td>
<td>23.67</td>
<td>2.62</td>
<td>4.01</td>
<td>0.72</td>
<td>17.82</td>
<td>51.17</td>
<td>43.46</td>
<td>10069.00</td>
</tr>
<tr>
<td>Liyan</td>
<td>20.45</td>
<td>4.20</td>
<td>1.96</td>
<td>0.40</td>
<td>23.58</td>
<td>49.40</td>
<td>43.76</td>
<td>7812.50</td>
</tr>
<tr>
<td>Sadesa</td>
<td>33.61</td>
<td>5.22</td>
<td>2.80</td>
<td>0.31</td>
<td>21.17</td>
<td>36.70</td>
<td>62.35</td>
<td>14240.17</td>
</tr>
<tr>
<td>Shuitou</td>
<td>26.12</td>
<td>3.67</td>
<td>1.34</td>
<td>0.98</td>
<td>23.58</td>
<td>51.17</td>
<td>43.76</td>
<td>7812.50</td>
</tr>
<tr>
<td>Shengxiong</td>
<td>30.37</td>
<td>3.22</td>
<td>2.80</td>
<td>0.88</td>
<td>23.58</td>
<td>49.40</td>
<td>43.76</td>
<td>7812.50</td>
</tr>
<tr>
<td>Dianchi</td>
<td>19.07</td>
<td>1.61</td>
<td>1.46</td>
<td>1.31</td>
<td>19.11</td>
<td>51.93</td>
<td>42.03</td>
<td>9883.10</td>
</tr>
<tr>
<td>Dongguan</td>
<td>14.51</td>
<td>2.30</td>
<td>2.20</td>
<td>0.50</td>
<td>13.07</td>
<td>66.95</td>
<td>29.39</td>
<td>5850.76</td>
</tr>
<tr>
<td>Jingyuan</td>
<td>26.42</td>
<td>3.15</td>
<td>1.20</td>
<td>4.75</td>
<td>13.07</td>
<td>51.06</td>
<td>47.70</td>
<td>10871.47</td>
</tr>
</tbody>
</table>

**Sludge in China:** Low organic content, Low heat value

<table>
<thead>
<tr>
<th>Sludge sources</th>
<th>(A_d) (%)</th>
<th>(V_d) (%)</th>
<th>(Q_{b,d}) (kJ/kg)</th>
<th>(Q_{b,d}) (kcal/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (China)</td>
<td>50.71</td>
<td>44.80</td>
<td>9813.03</td>
<td>2344</td>
</tr>
<tr>
<td>EU</td>
<td>20~40</td>
<td>60~80</td>
<td>16000~20000</td>
<td>3821~4777</td>
</tr>
<tr>
<td>Japan</td>
<td>24</td>
<td>76</td>
<td>17000</td>
<td>`4060</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sludge sources</th>
<th>(A_d) (%)</th>
<th>(V_d) (%)</th>
<th>(Q_{b,d}) (kJ/kg)</th>
<th>(Q_{b,d}) (kcal/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baiyun</td>
<td>23.06</td>
<td>1.59</td>
<td>0.25</td>
<td>19.60</td>
</tr>
<tr>
<td>Ruifeng</td>
<td>27.82</td>
<td>2.74</td>
<td>0.26</td>
<td>25.70</td>
</tr>
<tr>
<td>average</td>
<td>24.29</td>
<td>2.29</td>
<td>1.91</td>
<td>17.67</td>
</tr>
<tr>
<td>EU</td>
<td>20~40</td>
<td>60~80</td>
<td>16000~20000</td>
<td>3821~4777</td>
</tr>
<tr>
<td>Japan</td>
<td>24</td>
<td>76</td>
<td>17000</td>
<td>`4060</td>
</tr>
</tbody>
</table>
Thermal Drying: Necessary Step

- **Sludge to Energy:** thermal drying is a necessary step
- **After thermal drying,** the moisture content of sludge can reduce to 50% or even lower, the mass and volume of the sludge will decrease and the heat value will increase
Paddle dryer was always applied in chemical and food industries, which has been developed to be used in the sludge drying.

→ The wall, paddle and shaft are hollow filled with the steam.
→ The heat of the steam will be transferred to the sludge by contacting.
Contact Dryer: Sludge Stickiness?

Shear force

\[ \tau = \frac{(m-m_0) \cdot g}{A} \]

1. stainless steel plate, 2. electric heating panel, 3. hollow cylinder, 4. hook, 5. wire, 6. container, 7. weights, 8. wheel, 9. massive cylinder, 10. massive weight, 11. sludge cake, 12. circular ring
Adhesion and Cohesion of Sludge

The adhesion and cohesion force of two kinds of the sludge achieve the maximum in the moisture content range at 40%~65%
Test in Paddle Dryer
Sticky Behavior

- Moisture content 85%
- Moisture content 74%
- Moisture content 65%
- Moisture content 57%
- Moisture content 45%
- Moisture content 29%
- Moisture content 23%

- Drying rate (g/min·m²)
- Stirring power (kw)
- Sludge temperature (°C)
- Cohesion
- Adhesion
- Shearing force (N/m²)

Images show the effects of moisture content on various properties and behaviors.
Emission: Sludge sampling

- Emission from the drying and incineration is another important aspect

- WWTPs: mainly municipal wastewater, mix with a certain amount of industrial wastewater

- Waste water treatment techniques: Activated Sludge Process (A/O or A/A/O)

- Sludge dewatering method: pressure filtration or centrifugal dewatering
### Proximate and Ultimate Analysis

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Sludge</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Shenzhen</td>
<td>Shanghai</td>
</tr>
<tr>
<td><strong>Moisture content</strong></td>
<td>wt. %</td>
<td>76.46</td>
<td>83.85</td>
</tr>
<tr>
<td><strong>Proximate analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>%</td>
<td>52.75</td>
<td>35.64</td>
</tr>
<tr>
<td>Volatile</td>
<td>%</td>
<td>40.97</td>
<td>56.78</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>%</td>
<td>4.93</td>
<td>7.44</td>
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<tr>
<td>Heat value</td>
<td>kJ/kg</td>
<td>10159</td>
<td>15235</td>
</tr>
<tr>
<td><strong>Ultimate analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>%</td>
<td>25.14</td>
<td>41.90</td>
</tr>
<tr>
<td>H</td>
<td>%</td>
<td>4.23</td>
<td>5.52</td>
</tr>
<tr>
<td>N</td>
<td>%</td>
<td>2.84</td>
<td>4.53</td>
</tr>
<tr>
<td>S</td>
<td>%</td>
<td>0.74</td>
<td>1.18</td>
</tr>
<tr>
<td>O</td>
<td>%</td>
<td>12.93</td>
<td>11.09</td>
</tr>
<tr>
<td>Cl</td>
<td>mg/g DS</td>
<td>1.30</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Pilot-scale Sludge Paddle Dryer

2 tons/day
Lab-scale electrically heated fluidized bed incinerator
# Gaseous Emission during Sludge Drying

*(mg/Nm$^3$, dry base)*

<table>
<thead>
<tr>
<th>Gaseous pollutants</th>
<th>Shenzhen</th>
<th>Shanghai</th>
<th>Hangzhou</th>
<th>Shaoxin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SO$_2$</strong></td>
<td>2.317</td>
<td>4.012</td>
<td>6.324</td>
<td>6.181</td>
</tr>
<tr>
<td><strong>NH$_3$</strong></td>
<td>7.28</td>
<td>7.956</td>
<td>2.026</td>
<td>3.762</td>
</tr>
<tr>
<td><strong>HCl</strong></td>
<td>0.002</td>
<td>0.035</td>
<td>0.008</td>
<td>0.012</td>
</tr>
<tr>
<td><strong>HF</strong></td>
<td>0.002</td>
<td>0.009</td>
<td>0.011</td>
<td>0.056</td>
</tr>
<tr>
<td><strong>HCN</strong></td>
<td>0.014</td>
<td>1.210</td>
<td>0.239</td>
<td>0.936</td>
</tr>
<tr>
<td><strong>CH$_4$</strong></td>
<td>0.184</td>
<td>0.243</td>
<td>0.102</td>
<td>0.274</td>
</tr>
<tr>
<td>Formic acid</td>
<td>0.015</td>
<td>0.136</td>
<td>0.136</td>
<td>0.211</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>0.025</td>
<td>2.448</td>
<td>0.379</td>
<td>2.764</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>0.025</td>
<td>2.448</td>
<td>0.379</td>
<td>2.764</td>
</tr>
</tbody>
</table>

![Graph showing gaseous pollutants emissions in Shenzhen, Shanghai, Hangzhou, and Shaoxin](image)
Where they are from?

- **SO₂** and **NH₃** come from the sulfur and nitrogen in sludge

- The volatile fatty acids could be produced from hydrothermal of organic matters in sludge
### Dioxin in flue gas

<table>
<thead>
<tr>
<th>PCDD/Fs</th>
<th>Shenzhen</th>
<th>Shanghai</th>
<th>Hangzhou</th>
<th>Shaoxin</th>
<th>National regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3.7.8-TCDD</td>
<td>0.00569</td>
<td>0.0043</td>
<td>0.00010</td>
<td>0.0253</td>
<td></td>
</tr>
<tr>
<td>1.2.3.7.8-PCDD</td>
<td>0.01497</td>
<td>0.0033</td>
<td>0.00002</td>
<td>0.0653</td>
<td></td>
</tr>
<tr>
<td>1.2.3.4.7.8-HexCDD</td>
<td>0.00213</td>
<td>0.0002</td>
<td>0.00037</td>
<td>0.0099</td>
<td></td>
</tr>
<tr>
<td>1.2.3.5.7.8-HexCDD</td>
<td>0.00639</td>
<td>0.0014</td>
<td>0.00183</td>
<td>0.0137</td>
<td></td>
</tr>
<tr>
<td>1.2.3.7.8.9-HexCDD</td>
<td>0.00457</td>
<td>0.0035</td>
<td>0.00000</td>
<td>0.0178</td>
<td></td>
</tr>
<tr>
<td>1.2.3.4.6.7.8-HepCDD</td>
<td>0.00351</td>
<td>0.0011</td>
<td>0.00179</td>
<td>0.0062</td>
<td></td>
</tr>
</tbody>
</table>

**I-TEQ concentration (ng TEQ/Nm³)**

<table>
<thead>
<tr>
<th>PCDD/Fs</th>
<th>Shenzhen</th>
<th>Shanghai</th>
<th>Hangzhou</th>
<th>Shaoxin</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3.7.8-TCDD</td>
<td>0.00418</td>
<td>0.0028</td>
<td>0.00010</td>
<td>0.0291</td>
</tr>
<tr>
<td>1.2.3.7.8-PCDF</td>
<td>0.00156</td>
<td>0.0009</td>
<td>0.00312</td>
<td>0.0064</td>
</tr>
<tr>
<td>1.2.3.4.7.8-PCDF</td>
<td>0.02335</td>
<td>0.0141</td>
<td>0.02997</td>
<td>0.0464</td>
</tr>
<tr>
<td>1.2.3.4.7.8-HexCDF</td>
<td>0.00303</td>
<td>0.0010</td>
<td>0.00376</td>
<td>0.0039</td>
</tr>
<tr>
<td>1.2.3.4.7.8-HexCDF</td>
<td>0.00430</td>
<td>0.0008</td>
<td>0.01460</td>
<td>0.0032</td>
</tr>
<tr>
<td>1.2.3.7.8.9-HexCDF</td>
<td>0.00529</td>
<td>0.0010</td>
<td>0.00152</td>
<td>0.0064</td>
</tr>
<tr>
<td>2.3.4.6.7.8-HexCDF</td>
<td>0.00060</td>
<td>0.0003</td>
<td>0.00010</td>
<td>0.0016</td>
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</table>

**Contents (mg/g DS)**

<table>
<thead>
<tr>
<th>Cl contents (mg/g DS)</th>
<th>Shenzhen</th>
<th>Shanghai</th>
<th>Hangzhou</th>
<th>Shaoxin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.30</td>
<td>0.69</td>
<td>0.80</td>
<td>0.93</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S contents (%)</th>
<th>Shenzhen</th>
<th>Shanghai</th>
<th>Hangzhou</th>
<th>Shaoxin</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.74</td>
<td>1.18</td>
<td>3.09</td>
<td>6.10</td>
<td></td>
</tr>
</tbody>
</table>

| OCDF                  | 0.00008  | 0.00000  | 0.00075  | 0.0001  |
| I-TEQ concentration   | 0.082    | 0.030    | 0.069    | 0.237   |

Unit: ng TEQ/Nm³
# Heavy metals in flue gas

Sludge from Shenzhen

<table>
<thead>
<tr>
<th>Heavy metals</th>
<th>Concentration</th>
<th>Chinese regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>0.107</td>
<td>0.1</td>
</tr>
<tr>
<td>Hg</td>
<td>0.018</td>
<td>0.2</td>
</tr>
<tr>
<td>Pb</td>
<td>1.780</td>
<td>1.6</td>
</tr>
</tbody>
</table>
# Heavy metal leaching liquid

<table>
<thead>
<tr>
<th>Heavy metals</th>
<th>Contents</th>
<th>Leaching characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw sludge</td>
<td>Fly ash</td>
</tr>
<tr>
<td></td>
<td>mg/kg DS</td>
<td>mg/L</td>
</tr>
<tr>
<td>Cd</td>
<td>3.19</td>
<td>0.002</td>
</tr>
<tr>
<td>Hg</td>
<td>0.066</td>
<td>0.0032</td>
</tr>
<tr>
<td>Pb</td>
<td>89.73</td>
<td>0.057</td>
</tr>
<tr>
<td>Cr</td>
<td>644.8</td>
<td>15.35</td>
</tr>
<tr>
<td>Ni</td>
<td>290.0</td>
<td>0.003</td>
</tr>
<tr>
<td>Cu</td>
<td>434.4</td>
<td>0.019</td>
</tr>
<tr>
<td>Zn</td>
<td>1134</td>
<td>0.027</td>
</tr>
</tbody>
</table>

For the Chinese regulation for sludge: if the concentration of heavy metals in leaching liquid does not exceed to the limitation for the hazard waste, the fly ash can be recycled in the material industry, for example, cement industry.
Semi-drying and Incineration System

Indirect thermal dryer

Agitated dryer
ZL03114452.7
ZL201110183248.2
ZL201210042587.3

Low grade steam

Semi-adiabatic membrane wall

Demi-drying sludge

Fixed scraper

Inclined paddle

Angle adjustable blade

CFB incinerator

Combined circulation inside and outside the furnace
ZL201010122951.8
ZL201210189962.7

Pollutant control

Gas-solid separation

Vapor condenser

Activated carbon

Back to incinerator

Plasma degradation

Bag filter

To stack

Combined dioxin control technology
ZL200910095645.7
ZL200910096371.3

Wet sludge

Turbine
Paddle Dryer

- The heat source is 0.4-0.6MPa (150°C) saturation steam
- Hidden heat of the saturation steam is utilized, and the consumption of the steam is less than flue gas drying technique
- It is a kind of indirect drying technique. Steam has on contact with the sludge, and the waterish gas can be treated easily
Styles of paddle dryers

- New type of paddle
- Paddle angle can be adjusted
- Series from 10t/d ~ 150t/d
- Minimum heat loss
- Low energy consumption

One shaft (Disk)
Two shaft
Four shaft
Gas-solid separation

Vapor condensation

Plasma degradation

Incineration back to incinerator
CFB incinerator

Bubbling Fluidized Bed

- Temperature distribution: increase with the height
- Suspension section need spraying water to cool
- Low energy efficiency

CFB Technology

- Combined circulation inside and outside the furnace
- Semi-adiabatic membrane wall
- Hot-cold grading air supply
Traditional Pollutants

- **NOx**: 850°C~950 °C temperature, grading air supply
- **SO₂, HCl**: Furnace calcium base de-sulfur, semi-dry
- **CO**: Combustion optimization
- **PM**: Bag filter

Special Pollutants

- **Dioxins**:
  - “3T” control
  - Activated carbon and bag filter
- **HMs**: Activated carbon
Typical Application Solutions

- **Drying**
- **Incineration**
- **Heat utilization**
- **Pollution control**

- Sludge: Independent incineration
- Coal: Co-combustion with coal
- MSW: Co-combustion with MSW
Jia’aisi – co-fired in CFB boiler

- **Location**
  Jiaxing, Zhejiang Province

- **Year**
  2009

- **Sludge**
  The sewage sludge

- **Capacity**
  1000t/d

- **Routine**
  Sludge is dried to 45-50%, and co-fired in CFB boiler
Jia’aisi – co-fired in CFB boiler

- Sludge 1000 t/d (80% moisture)
- Coal 334 t/d (5000 kcal/kg)
- Sludge 334 t/d (40% moisture)
- Dryer
- Fuels Ratio:
  - Wet sludge: coal=4:1
  - Dried sludge: coal=1:1
- Steam 105 t/h (485°C, 5.3MPa)
- Ash 100 t/d

Diagram:
- Sludge 1000 t/d (80% moisture) → Dryer → Sludge 334 t/d (40% moisture) → incinerator → Steam 105 t/h (485°C, 5.3MPa) → Power 6MWe (Back pressure turbine)
- Coal 334 t/d (5000 kcal/kg) → incinerator
- Ash 100 t/d → Recycled

66 t/h (175°C, 0.981MPa)
39 t/h (175°C, 0.981MPa)
Jia’aisi – co-fired in CFB boiler
## Emission

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>Value</th>
<th>Chinese regulation</th>
<th>EU regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust</td>
<td>mg/Nm³</td>
<td>13.3</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>SO₂</td>
<td>mg/Nm³</td>
<td>45</td>
<td>260</td>
<td>50</td>
</tr>
<tr>
<td>HCl</td>
<td>mg/Nm³</td>
<td>3.37</td>
<td>75</td>
<td>10</td>
</tr>
<tr>
<td>CO</td>
<td>mg/Nm³</td>
<td>48</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>NOₓ</td>
<td>mg/Nm³</td>
<td>18</td>
<td>400</td>
<td>NO₂: 200</td>
</tr>
<tr>
<td>Hg</td>
<td>mg/Nm³</td>
<td>&lt;0.0011</td>
<td>0.2</td>
<td>0.05</td>
</tr>
<tr>
<td>Cd</td>
<td>mg/Nm³</td>
<td>&lt;0.0041</td>
<td>0.1</td>
<td>Cd+Ti: 0.05</td>
</tr>
<tr>
<td>Pb</td>
<td>mg/Nm³</td>
<td>&lt;0.043</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Dioxin</td>
<td>ng TEQ/ Nm³</td>
<td>0.004</td>
<td>1.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Jiaxing – co-fired in power plant

- **Location**
  Jiaxing, Zhejiang province
- **Sludge**
  Sewage sludge
- **Capacity**
  250t/d
- **Routine**
  Dried sludge as the fuel in the power plant of 300MWe
Pinghu – co-fired with waste paper

- **Location**
  Pinghua, Zhejiang province

- **Year**
  2009

- **Fuel**
  Sludge and waste paper

- **Capacity**
  Sludge 500t/d, waste paper 250t/d

- **Routine**
  Dried sludge with moisture content 40%, co-fired with waste paper
Shaoxing – co-fired in MSW incinerator

- **Location**
  Shaoxing, Zhejiang Province

- **Year**
  2008

- **Fuel**
  Sludge and MSW

- **Capacity**
  Sludge 1000t/d, MSW 1200t/d

- **Routine**
  Dried sludge with moisture content 40%, as the assistant fuel of MSW
Sludge 60 t/d (80% moisture)

Coal 2.32 t/d (5000 kcal/kg)

Steam 1.47 t/h

Ash 4.8 t/d

Dryer

Recycle

sludge:coal=1:0.039
### Other application of sludge drying and incineration in China

<table>
<thead>
<tr>
<th>Project name</th>
<th>Sludge Source</th>
<th>Treatment amount(tons/d)</th>
<th>Water content</th>
<th>Drying Heat source</th>
<th>Drying Temperature</th>
<th>Drying methods</th>
<th>Moisture content</th>
<th>Incineration Boiler</th>
<th>Incineration Temperature</th>
<th>Incineration Residence time</th>
<th>Auxiliary fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanghai Shidongkou waste water treatment plant</td>
<td>Sewage sludge</td>
<td>180</td>
<td>80%</td>
<td>Thermal Oil (Heat recovered from Boiler)</td>
<td>85℃</td>
<td>Fluidized bed dryer</td>
<td>&lt; 10%</td>
<td>Bubbling fluidized bed</td>
<td>&gt; 850℃</td>
<td>&lt; 2s</td>
<td>✓</td>
</tr>
<tr>
<td>Chongqing Tangjiatuo waste water treatment plant</td>
<td>Sewage sludge</td>
<td>192</td>
<td>75%</td>
<td>Thermal Oil</td>
<td>85℃</td>
<td>Thin-layer dryer+Belt dryer</td>
<td>10%-30%</td>
<td>-</td>
<td>1500℃</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beijing cement plant company</td>
<td>Sewage sludge</td>
<td>500</td>
<td>80%</td>
<td>Thermal Oil (Heat recovered from Boiler)</td>
<td>240℃</td>
<td>Thin-layer dryer</td>
<td>30%</td>
<td>Rotary kiln</td>
<td>&gt; 850℃</td>
<td>20s</td>
<td>-</td>
</tr>
<tr>
<td>Xiaoshan waste water treatment plant</td>
<td>Sewage sludge</td>
<td>360</td>
<td>80%</td>
<td>Exhaust gas</td>
<td>70℃-500℃</td>
<td>Spray dryer</td>
<td></td>
<td></td>
<td></td>
<td>&lt; 2s</td>
<td>-</td>
</tr>
</tbody>
</table>

- **Heat source**
  - Thermal Oil (Heat recovered from Boiler)
  - Thermal Oil
  - Thermal Oil (Heat recovered from Boiler)
  - Exhaust gas

- **Temperature**
  - 85℃
  - 85℃
  - 240℃
  - 70℃-500℃

- **Drying methods**
  - Fluidized bed dryer
  - Thin-layer dryer+Belt dryer
  - Thin-layer dryer
  - Spray dryer

- **Moisture content**
  - < 10%
  - 10%-30%
  - 30%

- **Incineration Boiler**
  - Bubbling fluidized bed
  - Rotary kiln
  - Rotary kiln

- **Incineration Temperature**
  - > 850℃
  - -
  - 1500℃
  - > 850℃

- **Incineration Residence time**
  - < 2s
  - -
  - 20s
  - < 2s

- **Auxiliary fuel**
  - ✓
  - -
  - ✓
  - -
In the fluidized dryer, the temperature of thermal oil is 180°C-220°C, while the temperature of sludge is 85°C. The distribution of sludge particle is uniform, the diameter is 1-5mm. Capacity: 213 ton/day. Operation cost: 280Yuan/ton.

Problem: Wear is heavy because a lot of sands in sludge.
Chongqing:

- Temperature of steam: 110℃
- Temperature of sludge: 85-95℃
- Dried by hot air at 100℃
- Capacity: 240 ton/day

Problem: Difficult to shape due to sands and impurities
Thank you for your attention!