Respect the Rheology!

Thickened Biosolids Pumping for Beneficial Reuse in Columbus, Ohio
December 7, 2017

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Senior Engineer, Brown and Caldwell
Agenda

- Overview of Columbus Biosolids Land Application Program/Project
- Sludge Pumping Design Practices
- Rheology 101
- Southerly WWTP Biosolids Land App Project
  - Field Testing
  - Rheology Testing
- Results and Startup
Overview of Columbus Biosolids Land Application Program
Columbus Sustainability Goals

• City sustainability goals described in the “Green Memo”

• Focus on conservation, efficiency, and renewables/reuse

• “Eliminate use of incinerators at Southerly WWTP...”
Southerly WWTP Solids Disposal

Southerly Biosolids Distribution 2014, Dry Tons

OM 2,453.58 18%
Incineration 2,574.80 19%
Liquid LA 0.00 0%
quasar 2,708.30 19%
Compost 6,171.60 44%

Southerly Biosolids 2015, Dry Tons

Incineration 592.88 4%
Deep Row Hybrid Poplar 3,620.95 26%
quasar 3,229.74 23%
Landfill 454.42 3%
Compost 6,070.03 44%

Southerly Biosolids 2017, Dry Tons

Grow Ohio 216.76 2%
Deep Row Hybrid Poplar 1,938.62 15%
Liquid LA 2,191.73 17%
quasar 4,001.49 32%
Compost 4,236.89 34%
SWWTP: 2017 (data through November)

- Liquid Land Application
  - 9,070,000 gallons
  - 37,400 wet tons
  - In Storage – 96,000 gallons
Biosolids Land Application

• Overview of BLAF project
  • 8 Mgal of storage for thickened biosolids
  • Truck loading station
  • Pump/control building for truck load out
  • Repurposed centrifuges/new thickened biosolids pumps

• Thickened biosolids:
  • Centrifuge thickened with polymer addition to 8-10% TS.
Two Thickened Biosolids (TBS) Pumping Systems Designed

TBS Transfer Pump
- From centrifuges to storage tanks

Truck Loading/Recirculation
- From tanks to truck loading, tank recirculation
The 8-million gallon question:

- How are we going to move this stuff (10%TS Biosolids)?
  - Not dry/typical cake %TS
  - Very thick (for a “liquid”), non-Newtonian characteristics.
The 8-million gallon question:
First... a little Rheology 101

- Newtonian Fluid: viscosity constant, independent of shear rate (water).
- Non-Newtonian: viscosity not constant with change in shear rate (Literature says wastewater sludge once solids concentration >~2%).
- Shear-thinning: viscosity decreases as shear-rate increases.
- Yield Stress: minimum amount of force (shear) applied to initiate flow.
- Thixotropy: viscosity decreases over time when constant shear is applied.
**Fluid Types/Behaviors**

- **“Pseudoplastic”**
  \[ \tau = K\gamma^n \quad \text{Power Law} \]
  \[ \tau = A\gamma + B\gamma^n \]

- **“Viscoplastic”**
  \[ \tau = \tau_y + K\gamma \]
  (Bingham Plastic)

- **“Viscous”**
  \[ \tau = K\gamma \]
  (Newtonian)
What do we know about biosolids?

• Review of literature suggests digested sludge acts like a viscoplastic.
  • Shear-thinning
  • Yield stress
What does that look like on system curve?

- **Yield Stress**, which must be overcome before the sludge will flow.

- High viscosity / friction at low flow causes steep slope in H-Q curve.

- Shear thinning, decreasing viscosity actually causes curve to dip as flow/velocity increase.

- Once fully turbulent (viscosity becomes constant), H-Q curve shape resembles water curve.
Let’s hit the books...

- Pumping Station Design (Sanks)
  - Underlying theory/equations
  - Pump types
  - Design procedures

- “Mulbargar Curves”

- Acknowledges uncertainty in sludge friction loss calculations and recommends adjusting factors upward by “50% or more” for atypical sludges.
What did we come up with?

- Textbook – “Mulbargar” approach (based on 10% TS):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TBS Transfer</th>
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<tbody>
<tr>
<td>Flow (gpm)</td>
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<td>Pressure (psi)</td>
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<td>Motor size, selected (hp)</td>
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<table>
<thead>
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### So... we’re done, right?

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**RESPECT THE RHEOLOGY!**

Motor size, selected (hp) 125
Too much uncertainty in sludge characteristics

- Two-pronged approach to improve our confidence in sludge pumping design:
  - Field testing
  - Rheology testing
Field Testing

• Centrifuge testing/optimization needed to produce 8-10% TS

• Existing thickened sludge pumps (rotary lobes) pumped to Digester 6 (digested sludge storage).

• Flow, pump speed, and manual pressure readings along the flow path. %TS grabs from centrifuges taken.
Field Testing - Findings

- Dialing in/maintaining at 9% or 10% is challenging.
- Existing TSPs were not going to be sufficient to pump all the way to the new storage tanks.
- Data was noisy.
  - Pump speed, flow, and pressure loss weren’t following clear relationship.
- Estimated pressure loss roughly based on psi/ft.
  - ~0.05 psi/ft at 55-75 gpm.
Rheology Analysis

- Field collected samples (at 9.6 %TS) sent to private lab
- Tested at two temperatures (40F and 75F)
- Tested over shear range of 0.01 to 100 s\(^{-1}\)
- STRESSTECH Rheometer (cup and bob)
Rheometers

Spindle type
Concentric cylinder
Double cone-plate
Cone-plate
Plate-plate
Cone-cone
Shear Thinning Behavior
Two 40°F Runs with Power Law and Bingham Fits

Shear Stress (Pa)

Shear Rate (s⁻¹)

\[ \tau = K\gamma^n \] (Power Law)

\[ \tau = \tau_y + K\gamma^n \] (Herschel-Bulkley)

\[ \tau = \tau_y + K\gamma \] (Bingham Plastic)

\[ \tau = K\gamma \] (Newtonian)
Rheology Results: Constants

• Bingham:
  • Yield Stress, $\tau_y \sim 70$ to 90 Pa
  • Consistency Factor, $K \sim 0.15$ to 0.24 Pa-s

• Power Law:
  • Consistency Factor, $K \sim 35$ to 65 (Pa-s)$^n$
  • Flow Index, $n \sim 0.13$ to 0.20
Avert your eyes... it’s math

- **Power Law – Laminar Case:**

\[
\begin{align*}
    & h_f = 4f \frac{L \overline{V}^2}{D} \\
    & f = \left( \frac{3n+1}{n} \right)^{n} \frac{2^{n+1}K}{\overline{V}^{2-n}D^n \rho} \\
    & \Delta p = -\frac{2^{n+2} \left( \frac{3n+1}{n} \right)^n LK\overline{V}^n}{D^{n+1}} \\
    & Re_{PL} = 2^{3-n} \left( \frac{n}{3n+1} \right)^n \frac{\overline{V}^{2-n}D^n \rho}{K} \\
    & Re_{PL,critical} = 2100 \frac{(4n+2)(5n+3)}{3(3n+1)^2}
\end{align*}
\]
Hopefully you know someone with a spreadsheet...

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Brown and Caldwell
## Updated Hydraulic Calculations - TBPs

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• Had to make sure piping class was OK
## Updated Hydraulic Calculations – Truck Loading Pumps

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</table>
Startup in Oct 2016

• Loaded 50 trucks during operational demonstration
• Pressure readings on the TBPs pumping to BLAF tanks up to 200psi
• Pumping from centrifuges to BLAF regularly since startup
• Over 9 million gallons pumped in 2017 through Nov.
Project Takeaways/Lessons Learned

• No mixing in storage tanks – only circulation
  • At least 4 turn-overs before sampling begins to get representative sample

• %TS decreases over time when stored – continued digestion?

• Great feedback from the haulers on the loadout station!
Summary of Best Practices for Design

• Sanks lays it out pretty well:
  1. Treat each sludge pumping application as a unique design problem
  2. Develop site specific design criteria based on detailed evaluation of the specific sludge characteristics.
• Establish range of operating conditions from clean water to worst case sludge scenario – especially for centrifugal pumps.
• Common sludges like raw, or digested, less than 5-6% TS – “textbook” or simplified approaches likely OK.
• If data exists for a “similar” sludge use it with caution.
• Hydraulic modeling softwares come with sludge correction/rheology models – apply with engineering judgement (do some homework on limitations/applicability).
When to do Rheology Testing?

- **Pumping design**
  - Especially for really thick or unusual sludge characteristics where data isn’t available.

- **Mixing designs**
  - Confirm how much energy is needed and if the sludge will mix
Thanks to everyone involved!

- **Black and Veatch**
  - Bob O’Bryan
  - Sierra McCreary
  - Tyler York

- **City of Columbus**
  - Troy Branson
  - Rick Kent
  - Everyone at SWWTP

- **Brown and Caldwell**
  - Dave Nitz
  - Dante Fiorino
  - Ravi Ravisangar (the man with the spreadsheet!)
Questions
Bullpen
More Rheology

- Shear Strain = $\delta u/h$
- Shear Stress = $F/A = \tau = N/m^2$
- Shear Rate (Shear Strain Rate) = $\delta$.Shear Strain/ $\delta$.time = s$^{-1}$
- Viscosity (dynamic or absolute) = Shear Stress/Shear Rate = $Ns/m^2$ (Pa-s or Poise)
- Kinematic (divide by density) = $m^2/s$ (Stokes)
Pump Types

- Centrifugal- Non-Clog
- Centrifugal- Recessed Impeller
- Screw-Centrifugal
- Progressive Cavity
- Rotary Lobe
- Piston Pumps
- Diaphragm