

Research Article

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Modeling thixotropic break-down behavior of dense anaerobically digested sludge

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Abstract: Mixing and homogenization in anaerobic digesters are affected by the flow curve of sludge. The aim of this study is to mathematically express the flow curve of dense anaerobically digested sludge behaving as thixotropic and pseudoplastic fluids. Time-dependent changes in two pseudoplastic parameters, i.e., consistency index (μ_p) and pseudoplastic index (n), by shear are modeled using a second-order kinetic equation with a coefficient that includes the power function of the shear strain rate. The calculated results are consistent with the experimental results. The kinetic parameters that yielded the ultimate values after shearing were associated with the sludge concentration, unlike the other kinetic parameters.

Keywords: non-Newtonian, Ostwald model, power law, high concentration, semi dry

1 Introduction

Anaerobic digestion is an important process for stabilizing and reducing excess sludge from wastewater treat-

ment plants. Recently, a high-concentration anaerobic digestion method has been reported that can increase the capacity, minimize the tank volume, and reduce the fuel for heating [1]. Mixing in anaerobic digesters is important for transferring substrates to microorganisms, ensuring a uniform pH and temperature, diluting inhibitory substances, and preventing stratification and short-circuiting. The mixing performance is significantly affected by the rheological properties of sludge in the tank [2].

For dense anaerobically digested sludge, some flow curve models have been introduced, e.g., the pseudoplastic model [3–6] and the Bingham model [7], both of which involve two flow curve parameters, and the Herschel–Bulkley (HB) model [8–11], which involves three flow curve parameters. When the relationship between sludge concentration and flow curve parameters is expressed using a pseudoplastic model, the consistency index (μ_p) increases and the pseudoplastic index (n) decreases as the sludge concentration increases [12]. The decrease in n with increasing sludge concentration indicates an increase in the effect of the physical interaction between the particles of a structure as well as an increase in the non-Newtonian property [13].

Biological wastewater sludge, such as anaerobically digested sludge, has been reported to exhibit a thixotropic [14–16], decreasing apparent viscosity with time under shearing, owing to the break-down of the floc structure [6,17–20]. Previously, thixotropy was mathematically expressed using the thixotropy parameter, λ [21]. Subsequently, using this model, the thixotropy of some actual fluids, drilling fluid [22], blood [23], waxy crude [24], maya crude oil [25], and fresh fluid concretes [26] were investigated. λ assumes a maximum value of 1 (structured) or smaller, depending on the destruction degree. The correlation of flow curve parameters with λ , yield stress [27,28], Bingham viscosity [29], and both yield stress and the Bingham viscosity [30,31] in the Bingham model or with the whole shear stress [32,33] has been expressed as a function of λ . Subsequently, viscosity expressed as a function of λ was included in a computational fluid dynamics (CFD) model, and the effect

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of time-dependent changes in viscosity by thixotropy on flow behavior was investigated [27,34].

Mixing is important for maintaining the performance of anaerobic digesters [35]. Because CFD models can estimate homogenizing times or velocity profiles, they are typically used to examine mixing [36–38]. To include the flow curve of sludge in CFD models, μ_p and n were defined as functions of sludge concentration [2,13,39]. The thixotropy of anaerobically digested sludge is presented only qualitatively in existing studies [6], where viscoelastic behavior is emphasized [40,41] or apparent viscosity is expressed as a function of time [42]. The change in the entire flow curve equation by shear as a function of time has not been presented. However, to express transient mixing phenomena such as stop mixing or start mixing using CFD models, mathematical expressions for changing the flow curve parameters with time and shear are necessary. Recently, Terashima *et al.* [43] proposed a model in which both μ_p and n change with time and attempted to apply it at limited sludge concentration. In this study, we applied this model to dense anaerobically digested sludge and investigated the sludge concentration dependencies of the model parameters.

2 Materials and methods

2.1 Sludge

Mesophilic anaerobically digested sludge was sampled from a municipal wastewater treatment plant. The sampled sludge was concentrated by centrifugation and then diluted to concentrations $C = 42, 54, 63, \text{ and } 70 \text{ g/L}$.

2.2 Flow curve measurement

A rheometer (RM100; Lamy Rheology, Lyon, France) with a spindle set MS-DIN 11 was used to measure the flow curves in this study. To obtain the curves, which depict the relationships between the shear strain rate and shear stress, the shear strain rate was increased stepwise by increasing the rotating speed of the spindle, and the shear stress was measured. The shear stress was measured thrice for the shear strain rate and then averaged. The shear strain ranged from 6.5 to 775 s^{-1} . The flow curves were measured before and after shearing.

2.3 Uprising thixotropy

Shear was given to the sludge to induce thixotropy using the flow curve measurement equipment. We applied a constant shear strain rate of $387, 904, \text{ or } 1,936 \text{ s}^{-1}$ over 2.5 h on each material and performed flow curve tests every 0.5 h to monitor its evolution over time. The time to obtain the flow curve is very short compared to the time to uprise thixotropy; therefore, the thixotropy effect by measuring flow curves was ignored.

2.4 Flow curve equation and thixotropy model

A pseudoplastic model (equation (1)) was used as the flow curve equation for anaerobically digested sludge as follows [2–6,13,39]:

$$\tau = \mu_p \dot{\gamma}^n, \quad (1)$$

where τ is the shear stress (Pa), μ_p is the consistency index (Pa s^n), $\dot{\gamma}$ is the shear strain rate (s^{-1}), and n is the flow behavior index (–).

The flow curves of anaerobically digested sludge can be approximated by the HB model [8–11], with three parameters including yield stress, or the simple pseudoplastic model [3–6], with only two parameters not including yield stress. In this study, we use the simple pseudoplastic model. One reason is that the HB model which has three parameters is too complicated to express the time-dependent change of these parameters, and also, it is too difficult to be mounted on the CFD. And the other reason is that the estimated yield stress in the HB model is estimated to be very small and R^2 values are almost the same between the HB model and the simple pseudoplastic model in our measurement results. This result is the same as reported by Cao *et al.* [44]. The model in this study should be carefully applied in the case the shear strain rate is out of range of this study.

To mathematically express the change in flow curve by shearing events, a structural parameter λ had been introduced, and some models have been developed to correlate λ with the flow curve equation [45]. In this study, thixotropy phenomena were modeled for two parameters, μ_p and n , in the pseudoplastic model. As the thixotropy parameter for μ_p , λ is defined as shown in equation (2), which is similar to an equation reported

by Hammadi et al. [33]. As the thixotropy parameter for n , κ is defined as shown in equation (3).

$$\lambda_{(t)} = \frac{\mu_{P(t)}}{\mu_{P0}}, \quad (2)$$

$$\kappa_{(t)} = \frac{1 - n_{(t)}}{n_0}, \quad (3)$$

where $\lambda_{(t)}$ is the time-dependent thixotropy parameter for μ_P , μ_{P0} is the initial consistency index (Pa sⁿ), $\kappa_{(t)}$ is the time-dependent-thixotropy parameter for n , and n_0 is the initial flow behavior index (–). The initial values of λ and κ were set to 1. After shearing, these values decreased. The rates are defined as a second-order reaction [33], and the coefficients are the power functions of shear strain rate with coefficients, as shown in equations (4) and (5), respectively.

$$\frac{d\lambda}{dt} = -\alpha_\lambda \dot{\gamma}^{\beta_\lambda} (\lambda - \lambda_e)^2, \quad (4)$$

$$\frac{d\kappa}{dt} = -\alpha_\kappa \dot{\gamma}^{\beta_\kappa} (\kappa - \kappa_e)^2, \quad (5)$$

where α_λ , β_λ , and λ_e are parameters for λ , α_κ , β_κ , and κ_e are parameters for κ . The initial values of λ and κ are 1 from (2) and (3), then these values monotonically decrease to these ultimate values, λ_e and κ_e , respectively. In case starting from intermediate state, these values start from smaller values than 1 and decrease to the ultimate value. In case starting from ultimate value, these values will not change.

Equations (4) and (5) were analytically solved under initial conditions $\lambda = 1$ and $\kappa = 1$ when $t = 0$. Subsequently, the solutions were substituted into equations (2) and (3), respectively, and equations (6) and (7) were obtained.

$$\mu_{P(t)} = \mu_{P0} \left(\frac{\alpha_\lambda (1 - \lambda_e) \lambda_e \dot{\gamma}^{\beta_\lambda t} + 1}{\alpha_\lambda (1 - \lambda_e) \dot{\gamma}^{\beta_\lambda t} + 1} \right), \quad (6)$$

$$n_{(t)} = 1 - (1 - n_0) \left(\frac{\alpha_\kappa (1 - \kappa_e) \kappa_e \dot{\gamma}^{\beta_\kappa t} + 1}{\alpha_\kappa (1 - \kappa_e) \dot{\gamma}^{\beta_\kappa t} + 1} \right), \quad (7)$$

where t is the shearing time. Based on Equations (6) and (7), μ_P and n can be calculated after shearing using $\dot{\gamma}$ and t . The kinetic parameters were calibrated with the measured datasets by fitting.

3 Results

The rheological curves for the shearing time and shearing rate are shown in Figures S1–S3, and S4 for $C = 42, 54, 63$, and 70 g/L, respectively. For all sludge concentrations, τ

in terms of $\dot{\gamma}$ decreased with shearing time; therefore, thixotropy was observed. The higher the shearing rate, the more significant was the decrease. In these flow curves, the flow curve parameters μ_P and n were determined using equation (1) by fitting.

The changes in μ_P and n with shearing time are shown in Figures 1 and 2, respectively. The error bars show the 95% confidential range in the fitting of μ_P and n . μ_P decreased with the shearing time, and the rate of decrease decreased as well; n increased with the shearing time, and the rate of increase decreased. The changes were significant when the shear was large. The changes in μ_P and n with time under shearing were calculated and fitted using equations (6) and (7), respectively. The calculating results fitted well with the experimental results. Only two kinetic parameters, i.e., λ_e and κ_e , vary with C , as shown in Figure 3. The other parameters remained constant, i.e., $\alpha_\lambda = 0.00122$, $\beta_\lambda = 1.28$, $\alpha_\kappa = 0.02643$, and $\beta_\kappa = 0.9697$.

4 Discussion

Thixotropy phenomena and a decrease in apparent viscosity with time under shearing were observed, as shown in Figures S1–S4, in anaerobically digested sludge, similar to previous reports [6,42]. Furthermore, in this study, it is clear that not only μ_P but also n changed with time under shearing. The presented models, which pertained to only yield stress [27,28], only Bingham viscosity [29], both of them [30,31], or whole shear stress [32,33] as a function of λ , did not support the abovementioned finding. However, the results obtained using the proposed model supported the finding and fitted the measured results well.

The developed model in this study is for anaerobically digested sludge, pseudoplastic flow curve. This model cannot be applied to yield stress flow curve. Time-dependent yield stress model [27,28,46] should be adapted for yield stress flow curve.

Models of both μ_P and n changed by shear with time have been recently proposed [43]. In this study, we applied these models to dense anaerobically digested sludge and clarified the relationship between the sludge concentration and model parameters. The kinetic parameters that yielded the ultimate values after shearing were associated with the sludge concentration, unlike the other kinetic parameters. The two kinetic parameters (λ_e and κ_e) were a function of the sludge concentration; they are the ultimate thixotropic parameters for the flow

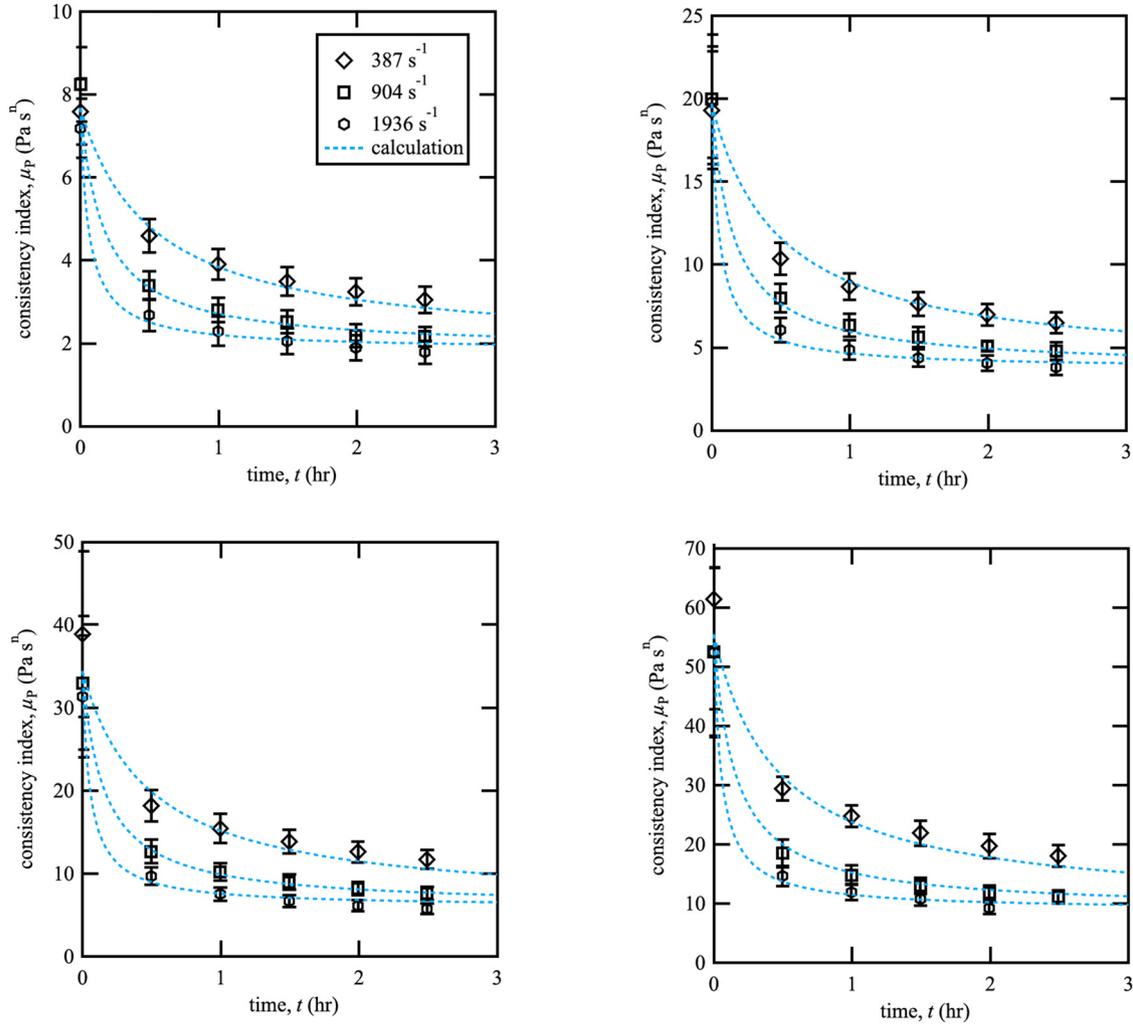


Figure 1: Change in μ_P with shearing time, $C = 42$ g/L (upper-left), $C = 54$ g/L (upper-right), $C = 63$ g/L (bottom-left), and $C = 70$ g/L (bottom-right).

curve parameters μ_P and n , respectively. Here, λ_e is the ultimate value of λ after shear, λ is the time-dependent thixotropy parameter for μ_P , κ_e is the ultimate value of κ after shear, and κ is the time-dependent thixotropy parameter for n . The reason for the fact that two ultimate kinetic parameters (λ_e and κ_e) were found to be fixed value independent of the adding shear strain rate may be that the dynamic range of adding shear strain rate is not large in this study. In case the adding shear is extremely small, out of the range of this study, the structure may not be destroyed or the structure may be no sooner build up than it is sheared; therefore, different values of λ_e and κ_e may be observed. The model in this study should be carefully applied in the case the shear strain rate is out of range of this study.

Thixotropic fluid has been reported after shearing is stopped, restructuring is performed, and apparent viscosity is increased. The thixotropy phenomena have

break-down and build-up. In this study, only break-down was measured and modeled. To model the build-up phenomena, the increase in λ and κ under small shear condition should be expressed in equations (4) and (5).

To apply this study to CFD models, λ and κ should be defined as variables in the fluid, the advection–reaction equation for λ and κ should be solved. Subsequently, the change in apparent viscosity with time under shearing can be included in the calculation of the anaerobic digester.

5 Conclusion

The aim of this study was to mathematically express the flow curve of dense anaerobically digested sludge behaving as thixotropic and pseudoplastic fluids. The time-dependent changes in the pseudoplastic parameters,

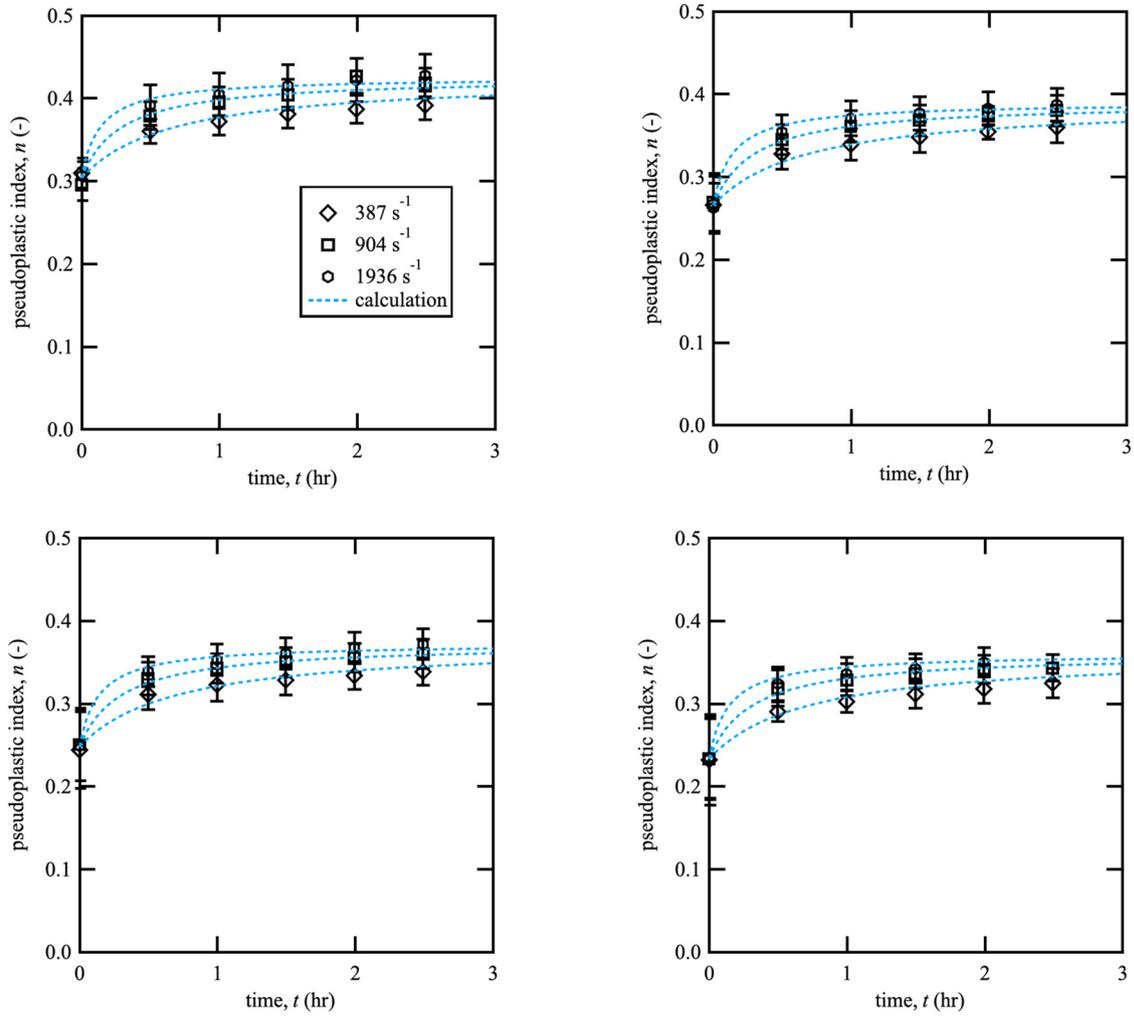


Figure 2 : Change in n with shearing time, $C = 42$ g/L (upper-left), $C = 54$ g/L (upper-right), $C = 63$ g/L (bottom-left), and $C = 70$ g/L (bottom-right).

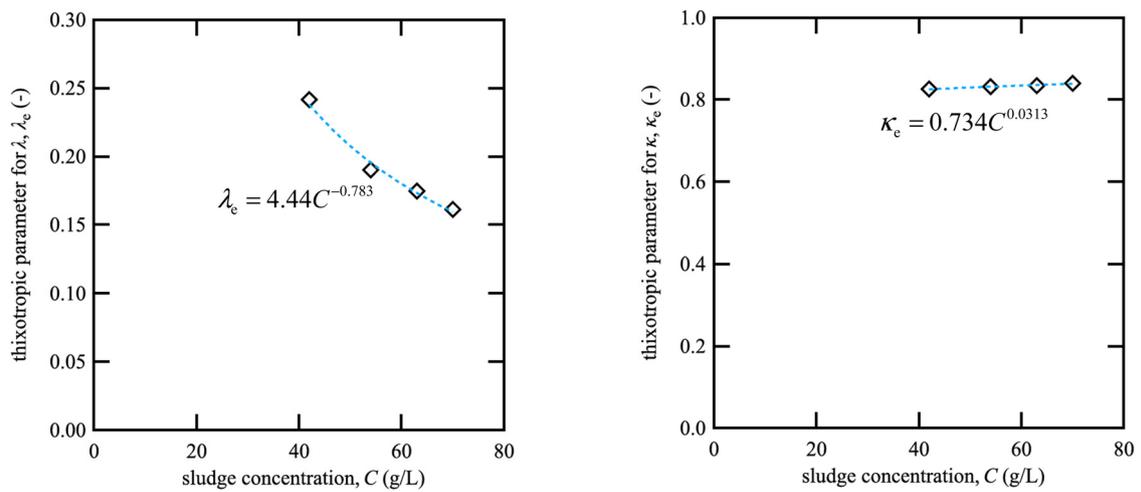


Figure 3 : Change in thixotropic parameters, λ_e (left) and κ_e (right) with C .

i.e., μ_p and n by shearing were modeled using a second-order kinetic equation with a coefficient, including a power function of the shearing rate. The calculating results fitted well with the experimental results. The kinetic parameters that yielded the ultimate values after shearing were associated with the sludge concentration, unlike the other kinetic parameters.

The models proposed in this study well fit the measured results; time-dependent changes of μ_p and n for dense anaerobically digested sludge by shearing. In this study, the changes of thixotropy parameters, λ and κ , were modeled and the reaction rates were made clear. To apply this model to CFD, λ and κ should be defined as variables in the fluid, the advection–reaction equation for λ and κ should be solved. Subsequently, the flow in anaerobic digester can be calculated including the changing of flow curves of dense anaerobically digested sludge.

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