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# Impact of temperature and duration of thermal treatment on different concentrations of anaerobic digested sludge: Kinetic similarity of organic matter solubilisation and sludge rheology

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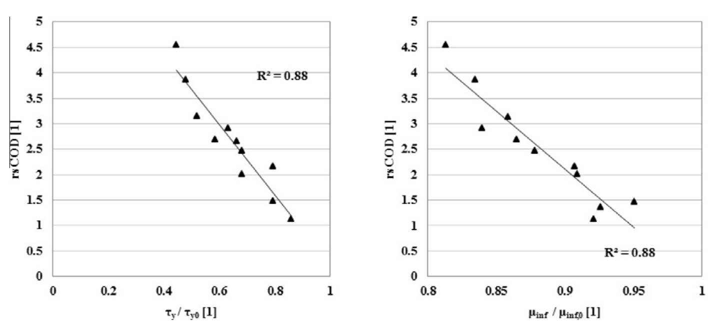
## HIGHLIGHTS

- When sludge undergoes thermal treatment.
- The rate of COD solubilisation increases logarithmically with treatment time.
- Yield stress & apparent viscosity decreases logarithmically with treatment time.
- The increase of rsCOD is proportional to the yield stress & apparent viscosity reduction.

## GRAPHICAL ABSTRACT

Linear relationships between released soluble COD and rheological properties (yield stress and apparent viscosity) of thermally-treated digested sludge.

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## ABSTRACT

Municipal digested sludge is a dispersion of agglomerated particles or flocs in a liquid medium which exhibits yield stress, shear thinning behaviour and high irreversible temperature dependence.

In this study, the rate of solubilisation of organic matter in digested sludge was investigated when sludge (at different solid concentrations) was exposed to thermal treatment between 50 and 80 °C for 1 to 60 min. The organic matter solubilisation was measured using chemical oxygen demand (COD) analysis on liquor of the thermally treated sludge. The effects of the abovementioned temperature range and heating duration on yield stress and the apparent viscosity of sludge at different solid concentrations have also been investigated.

The results showed that the irreversible effect of temperature was much higher at higher concentrations, higher temperatures and longer duration of treatment. It was also observed that for any sludge concentration the kinetic of COD solubilisation, yield stress and apparent viscosity reductions followed a logarithmic correlation with duration of thermal treatment. This similarity was also pronounced in the linear relationship between solubilised COD and yield stress and apparent viscosity reductions in all tested concentrations and the durations of heat treatment. Modified form of Herschel–Bulkley was used to obtain a master curve, independent of temperature, concentration and duration of thermal treatment. Furthermore, a new model was proposed for the impact of temperature and the duration of thermal treatment on yield stress and apparent viscosity reduction.



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**Nomenclature**

| | |
|---|---|
| $T$ | temperature [°C] |
| $T_{th}$ | temperature of thermal history [°C] |
| $t$ | duration time of thermal treatment [min] |
| $t_{th}$ | duration time of thermal history [min] |
| $\tau$ | shear stress [Pa] |
| $\tau_y$ | measured yield stress [Pa] |
| $\tau_H$ | calculated modified Herschel–Buckley yield stress [Pa] |
| $\tau_{H0}$ | calculated modified Herschel–Buckley yield stress at 20 °C [Pa] |
| $\dot{\gamma}$ | shear rate [$s^{-1}$] |
| $\Gamma$ | dimensionless shear rate |
| $k$ | consistency index of modified Herschel–Buckley [Pa $s^n$] |
| $K$ | consistency index of dimensionless modified Herschel–Buckley |
| $K_0$ | consistency index of dimensionless modified Herschel–Buckley at 20 °C |
| $n$ | power index of Herschel–Buckley |
| COD | chemical oxygen demand [mg/L] |
| rsCOD | released soluble COD |
| wt.% | sludge concentration on weight basis |
| $\alpha$ | high shear rate viscosity of modified Herschel–Bulkley |
| $\alpha_0$ | high shear rate viscosity at 20 °C |
| $\mu_{inf}$ | infinite viscosity [Pa s] |
| $\mu_{inf,0}$ | infinite viscosity at 20 °C [Pa s] |
| $\mu$ | apparent viscosity [Pa s] |
| TS | solid concentration [%] |
| $TS_0$ | the lowest concentration that there is no yield stress |

## 1. Introduction

In recent years, the amount of wastewater sludge to be treated has increased significantly leading to demands for increasing the efficiency of wastewater treatment plants. Moreover, a large portion of biogases (e.g. $CH_4$) contributing to climate change is produced and emitted during sludge treatment and landfilling [1]. To mitigate these issues, many researchers have suggested increasing the efficiency of wastewater treatment process using anaerobic digestion as well as implementing a thermal pre-treatment process [2].

The application of anaerobic digester has increased since the anaerobic digestion can significantly reduce the volumes of wastewater sludge to be disposed and it controls and captures the biogases. The anaerobic digester also reduces the adverse effects of organic waste by eliminating the objectionable matter in sludge such as pathogens and odour [3]. Moreover, the biogases including methane and carbon dioxide which are the useful by-products of anaerobic digestion can be burnt to produce both heat and electricity. The anaerobic digester operates either under mesophilic (35–38 °C) or thermophilic (55–58 °C) conditions [4] at high or low solid concentrations [5].

Rheological properties of sludge play key roles in sludge management and treatment [6] since they are being used in design of aerobic and anaerobic digesters, pumps and pipes [7], heat exchangers, sludge dewatering and biogas production units [8,9]. Sludge is known as a shear thinning, temperature dependant material which makes its rheological characterisation complicated when the sludge is being heated and recirculated for periods of several days during the anaerobic digestion process [10–12].

Many researchers have documented that increasing the temperature of sludge decreases the apparent viscosity and yield stress of sludge [11,13,14]. The Arrhenius-type equation has been used to describe the effect of temperature on viscosity by many researchers [15–17]. However the use of Arrhenius equation for sludge was recently objected by Baudez et al. [11] who suggested that there are some irreversible changes in sludge composition with thermal history. Farno et al. [18] proved that the solubilisation of organic matter due to thermal treatment irreversibly changes sludge structure and consequently its rheology as the percentage of released soluble COD at different temperatures was proportional to the yield stress decrease and the infinite viscosity increase. Many other researchers [19–21] also showed that low temperature thermal treatment of sludge (<100 °C) transfers organic matter from particulate form to a solubilised one and observed an increase in the soluble COD as a result of cell lysis.

This paper looks at the rate of organic matter solubilisation at different concentrations of digested sludge (2–7.2%) and at different treatment times (1–60 min) and its effects on rheological properties of sludge. The yield stress and the apparent viscosity were measured for different concentrations of sludge at different temperatures and durations of heat treatment. The soluble COD analysis showed that an increase in sludge concentration intensified the irreversible compositional changes with temperature and treatment time. In parallel, the same trends were observed with irreversible rheological changes as both yield stress and apparent viscosity reductions were much more evident at higher concentrations. Lastly, there was a similar kinetic between COD solubilisation and sludge rheology at different temperatures and concentrations as a direct relationship between increased solubilized COD and yield stress and apparent viscosity reductions was found with increasing treatment time. Based on these results, a new model for the impact of temperature and the duration of thermal treatment on yield stress and apparent viscosity was developed.

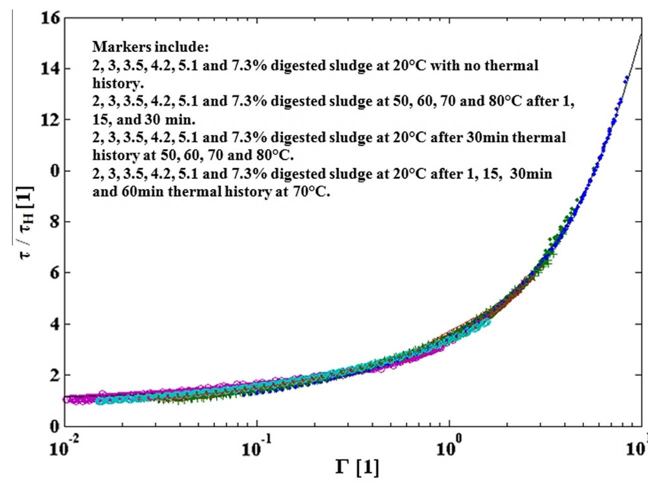


**Fig. 1.** Dimensionless master flow Curve of digested sludge (2–7.3%) at different temperatures and thermal histories (20–80 °C for 1–60 min); 2% digested sludge was used as a reference curve (Herschel–Bulkley Model: $\tau_{H0}$ = 0.87 Pa, $(\alpha_0)_{at\ 20°C}$ = 0.006 Pa s, $K_0$ = 1.4, $n$ = 0.5).

## 2. Materials and methods

The 2 wt% digested sludge was collected from Mount Martha waste water treatment plant (Melbourne, Victoria, Australia). The samples were stored at 4 °C for about 30 days to ensure that our samples were not changing during the tests [22]. The sludge was