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Relations Among Sludge Rheological Properties And Operational Problems In An Industrial Zone Wastewater Treatment Plant

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***Abstract*—The main objective is to examine how the viscosity values change in order to solve the problems frequently encountered in transmission lines in this study. Sludge samples from chemical and biological treatment process were taken in two different stages of nearby industrial zone wastewater treatment plant (IZWWTP). Physical, chemical and rheological properties of sludge samples were investigated in two different seasonal periods (October and February). The pH, temperature, conductivity, total suspended solid, chemical oxygen demand and total volatile solids of the sludge samples were determined in the first phase of the study. In the second phase, the shear stress and viscosity of the samples were determined to different shear rates using Brookfield DV-II+Pro viscometer. The rheological behaviors were modelled using Bingham, Ostwald and Herschel-Bulkley. In operating periods when viscosity increases, alternative coagulants may be preferred, chemical type or amount may be changed in the chemical process. Sludge pumps within the facility should be selected according to the rheological properties of the treatment sludge. Seasonal operating measures to be taken according to rheological properties can reduce operating costs.**

Keywords*— industrial wastewater sludge, modeling, non-Newtonian fluid, rheology, viscosity

I. INTRODUCTION

Industrial zones, where different production sector are located together, can bring many environmental risks. One of the most important risks is wastewater originating from industrial facilities. In order to protect water resources, wastewater collected from facilities is treated in industrial zone wastewater treatment plant (IZWWTP) established in industrial zones. Due to the joint treatment of wastewater with different properties originating from different sectors, IZWWTP consist of three stages namely physical, chemical and biological. Especially at the end of chemical and biological processes, large amounts of waste sludge are formed [1, 2]. The water content of sludge, which has a high volume, is 99% [2]. The solid matter content of the sludge is increased by processes such as dewatering, anaerobic digestion, thickening, conditioning [3] and final disposal is provided with transfer to the solid waste landfill area [4].

Understanding the rheological properties of the sludge has great importance for designing the transfer systems in the treatment plant [5], monitoring the control points in order to operate the plant efficiently [6, 7], increasing the efficiency of the sludge dewatering units [8, 9]. Rheological characterization of the sludge can be measured by plotting shear stress as a function of the shear rate [10]. Waste sludges exhibit Newtonian rheological property like water at low solids concentrations and non-Newtonian behavior at high solids concentrations [11]. Mathematical models most used to represent the behavior of non-Newtonian sludge mixtures are Power Law, Bingham, Casson, Herschel-Bulkley and Sisko models. The Power Law Model and Bingham Model are the most widely accepted models to determine the rheological character of concentrated suspended sludge samples [10, 12 – 15].

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Investigations on the rheological behavior of industrial sludge have been scarce, most of the studies deal with the sewage sludge and anaerobic digested sludge [13, 16]. Only Krylow and Fryzlewicz-Kozak (2007) have included the industrial wastewater in their study, determining the rheological properties of sludge before and after anaerobic digestion of domestic and industrial wastewater treatment plants [17]. However, there are few relevant studies, in particular for the inorganic conditioned or industrial zone wastewater sludge. Particularly, in a central IZWWTP, where the wastewater of seasonally operated factories is treated, the rheological properties of the sludge is changing, thus causing problems in the sludge transmission lines and dewatering processes. Considering the rheological properties of the treatment sludge, more efficient conditions can be achieved in the operation of the treatment plant.

Especially in autumn, problems of sludge monopump failure and clogging in sludge transmission lines are encountered in the Isparta Suleyman Demirel IZWWTP. The main objective of the study is to examine how the seasonal viscosity values change in order to solve the problems frequently encountered in transmission lines. The rheological properties of chemical and biological treatment sludge samples collected in different seasons were investigated.

II. Material and Methods

A. Sludge Samples

Samples were obtained from Isparta Suleyman Demirel IZWWTP as chemical treatment sludge (CTS) and biological treatment sludge (BTS). Due to the seasonal operations of some factories in the industrial zone, the incoming wastewater characteristics of the treatment plant also vary seasonally. Therefore, sludge samples were taken in February and October. While the February incoming wastewater content mainly consists of milk, fish and textile factory wastewater, in October, in addition to the existing three sources, wastewater from fruit (especially apple) juice production also reaches the wastewater treatment plant. Samples from the sludge thickener unit were not included in the study because it was not operational during the sampling periods due to equipment malfunctions.

B. Chemical Analysis

Chemical experiments were carried out on the collected sludge samples in order to determine conductivity with conductivity meter (Germany, WTW GmbH, model Level 1), temperature and pH values with pH meter (model 340i, WTW GmbH, Germany), volatile solids concentration (VSS), total suspended solids (TSS) parameters according to available standards [18]. The samples collected were subjected to experimental processes on the same day.

C. Rheological Analysis

Brookfield DV-II + Pro model viscometer was used to determine the rheological properties of collected sludge samples. LV4 spindle with 16 ml fixed volume at 20 ºC constant temperature was used due to the high solids content of the sludge. The device can measure very low viscosities owing to the spindles that can rotate at different speeds. The spindle to be used with the viscometer device software was calibrated before the experimental procedures.

The changes in apparent viscosity in the specified shear rate ranges (1-200 RPM) were recorded in the time to stop mode. The shear rate was increased linearly from 1.22 to 244.60 s^{-1} in 10 minutes using the following intervals: 1.22 s^{-1}, 1.83 s^{-1}, 3.67 s^{-1}, 7.34 s^{-1}, 14.68 s^{-1}, 36.69 s^{-1}, 73.38 s^{-1}, 122.30 s^{-1}, 183.45 s^{-1}, 244.60 s^{-1}, and the resulting shear stress and viscosity were recorded every 60 seconds. All measurements were carried out at room temperature (20±1 ºC). The evaluation has been done by performing three parallel analyzes on the samples taken in October and February. The shear stress and shear rate values were calculated using the formulas given by the manufacturer and the literature [19] utilizing the torque values. The axis dimensions used in the formula are the values given by the manufacturer for the relevant product.

Shear rate = 1.223*(RPM)

Shear stress = Torque / ((2) *(Spindle radius) (0.1588) *Spindle length(L) (3.396)

A wide variety of models have been presented in literature to examine rheological behavior of treatment sludges. The data collected during the study were fitted to the Bingham model (linear with yield), the Ostwald model (power) and the Herschel-Bulkley (power with yield) models, represented by equations 1,2 and 3, respectively [6, 11, 12, 20, 21].

$$\tau = \tau_0 + \eta_\pi \gamma \quad (1)$$

$$\tau = k \gamma n. \quad (2)$$

$$\tau = \tau 0 + k \gamma n \quad (3)$$

Where;

τ = shear stress (mPa)

τ_0= yield stress (Mpa),

k = consistency index (mPa.s^n)

η_p = plastic (limit) viscosity (mPa.s),

γ = shear rate (s^{-1})

n= flow behavior Index (-)

Parameters of all models were determined by IBM SPSS 20.0 statistical software using non-linear regression modeling. F-test was used in order to approve the statistical significance.

III. Results and Discussions

A. Chemical Characterization of Sludges

Some physical and chemical properties of CTS and BTS collected from IZWWTP in October and February were given in Table 1. The TSS concentrations of all samples are found to be significantly different. The TSS concentrations of chemical treatment sludge for February and October are 5928 mg/L and 8316 mg/L, respectively. The TSS concentrations of biological treatment sludge for the same months are 3316 mg/L and 4427 mg/L, respectively. The fruit juice production facility of the industrial zone starts to operate in October and wastewater containing high amounts of inorganic pollutants are released during the washing processes of low-quality apples coming from the gardens, especially in apple juice production. Since the wastewater originating from the fruit juice production facility is included in the process, TSS concentrations determined in October are higher than those determined in February. Higher COD values (Table 1) are also an indicator of high amount of organic and inorganic pollutants in the chemical sludge samples taken in October.

TABLE I. PROPERTIES OF SLUDGE SAMPLES COLLECTED IN OCTOBER AND FEBRUARY

Parameter	October		February	
	CTS	***BTS***	***CTS***	***BTS***
Chemical oxygen demand (COD) (mg/L)	38241	13265	24549	8462
Total suspended solid (TSS) (mg/L)	8316	4427	5928	3316
Volatile suspended solid (VSS) (mg/L)	61.54	84.37	58.92	81.13
pH	7.08	8.15	6.96	7.53

Parameter	October		February	
	CTS	***BTS***	***CTS***	***BTS***
Conductivity μS/cm	1671	1182	1425	975
Temperature ºC	20	20	20	20

VSS concentration value is an important parameter as it expresses the organic part of the solid matter contained in the sludge [22]. Since VSS concentrations of both chemical and biological treatment sludges were higher for October, it is most likely to contain inorganic and organic pollutants coming from apple washing. Apple production is intense in the region where the treatment plant is located. Apples used for juice production are mostly products that fall to the ground and become contaminated by both fertilizer and soil. The increase in VSS concentrations in October can be attributed to the wastewater content of the fruit juice production facility.

Conductivity is a general indicator of dissolved salt and can be used to monitor processes in the wastewater treatment that causes changes in total salt concentration and thus changes the conductivity. The main processes that reduce conductivity in wastewater treatment are biological nutrient removal [23]. The high amount of inorganic matter occurred in October for both treatment sludges could be the source of the increase for the conductivity values.

B. Rheological Bheavior of Sludges

Rheograms (Fig 1) show shear stress of the sludge samples as a function of shear rate. For all sludge samples, the shear stress increased as the shear rate increased. The increase is not linear. It is clear to see that the sludge samples exhibit a pseudoplastic behavior because $n<1$. It is a well-accepted phenomenon a that most activated wastewater sludge samples show pseudoplastic non-Newtonian behavior [17, 19]. Pseudoplastic behavior, also known as shear thinning, is the most common non-Newtonian flow type [14, 19, 24]. When the rheograms for all sludge samples are examined in Fig 1 and 2, it is seen that the apparent viscosity decreases and the shear stress increases with increasing shear rate.

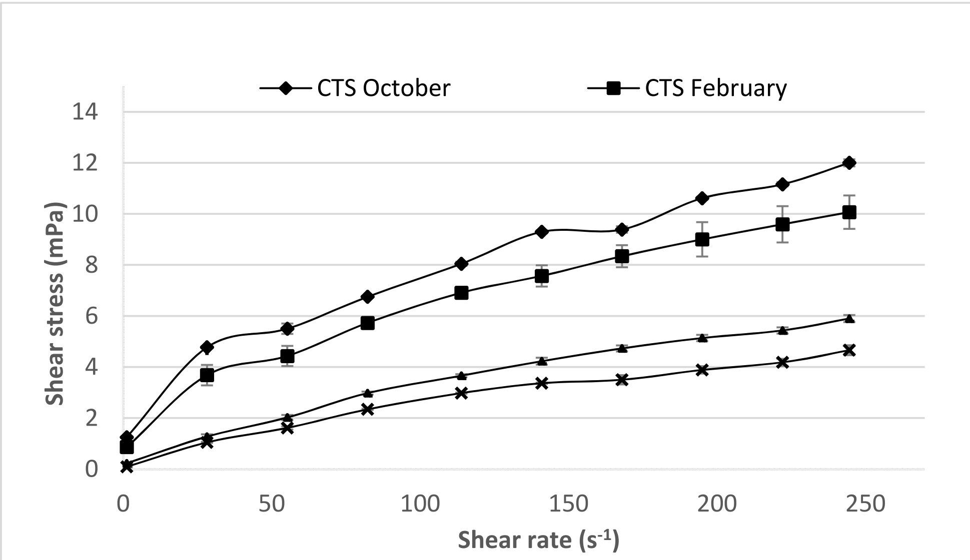

Fig. 1. *Shear stress of sludges at two seasonal periods*

The following parameters influence the viscosity of the sludge samples; suspended solids or solid concentration which is accepted as the most important parameter [7, 12, 15, 25], applied shear [26], yield stress, temperature [8, 16], particle size distribution, fluid consistency coefficient (k), sludge type, treatment process [6, 15, 27].

The apparent viscosity of the sludge samples examined in the study is strongly dependent on the origin. Heterogeneity of activated sludge samples among the water treatment plants is also reported in the literature [28, 29]. As presented in Fig 2, when the viscosity values of the sludge samples at constant shear rate are compared, the increasing solid substance concentration causes the initial viscosity values to be higher. As a matter of fact, $CTS_{October}$ and $CTS_{February}$, which have high suspended solids content, have high viscosity values. $FeCl_3$ is used as a coagulant in the chemical treatment unit of the wastewater treatment plant. Lime should be added to the chemical treatment unit in order to increase the decreasing pH values to neutral levels following the addition of the coagulant. This application may contribute to the increase of the viscosity of the CTSs. The use of alternative coagulants may be preferred during operating periods when viscosity increases.

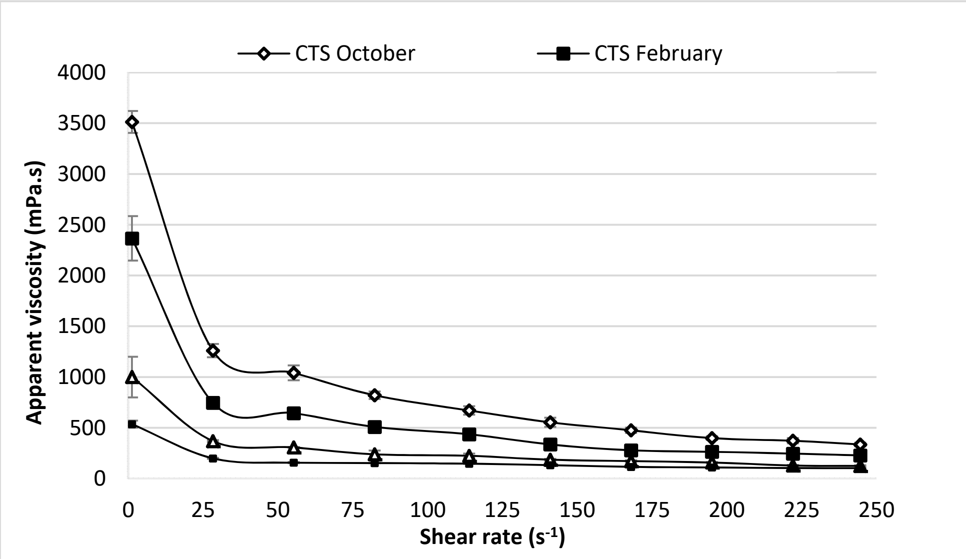

Fig. 2. *Rheogram of apparent viscosity as shear rates*

According to the literature review, poly aluminum chloride (PAC) seems to be more advantageous than $FeCl_3$ in terms of preventing the problems caused by viscosity increase [30]. At the same time, PAC provides higher removal efficiency in terms of both COD and turbidity compared to $FeCl_3$. [31 – 33].

According to Fig 2, all sludge samples presented thixotropic flow because apparent viscosity was decreased depending on shear rates. Higher solids content is generally responsible for higher viscosity and higher shear stress [2, 7, 8, 12]. An increase of solid concentration also causes an increase in sludge non-Newtonian behavior [25]. A high amount of TSS concentration yields to higher viscosity, thus effecting energy consumption and process control [14].

Non-Newtonian behavior of activated sludge samples can be explained by the deterioration of the floc structures at increasing shear rates. In activated sludge samples with high mixed liquor suspended solid concentrations, water retention increases due to cross-link structures in the floc structures. Increasing shear rates cause the deterioration of this structure and the resulting water causes a decrease in viscosity [26, 34]. Chemical treatment sludge of treatment plant showed similar pseudoplastic non-Newtonian flow characteristics. This can be attributed to the fact that the structure of the chemical treatment sludge has a dense floc structure due to the coagulant chemical used in the coagulation-flocculation process [35]. Especially sludges containing inorganic solids show thixotropic properties [35, 36].

Model parameters of the sludge samples collected in the study are given in Table 2. In all the analyzed sludge samples, the R^2 values are close to 1 which means that all models have good prediction capability.

TABLE II. MODEL PARAMETERS OF SLUDGE SAMPLES

Sample	Ostwald			Bingham			Herschel-Bulkley			
	k	***n***	R^2	τ_0	η_p	R^2	***k***	***n***	τ_0	R^2
$CTS_{October}$	0.897	0.467	0.991	3.002	0.039	0.943	0.615	0.526	0.688	0.993
$CTS_{February}$	0.637	0.501	0.997	2.311	0.034	0.948	0.512	0.536	0.336	0.998
$BTS_{October}$	0.151	0.668	0.996	0.747	0.022	0.971	0.157	0.661	-0.032	0.996
$BTS_{February}$	0.130	0.648	0.993	0.599	0.017	0.961	0.160	0.614	-0.131	0.994

In general, the Bingham model yielded lower R^2 values than the Ostwald model and the Herschel-Bulkley model indicating lower prediction capacity. In addition, Herschel-Bulkley model resulted negative τ_0 for biological sludges, which is physically not possible. Thus, Ostwald model seems to be most appropriate model for representing rheological behavior of the sludge samples collected in the study.

According to Oswald model, with the increase in shear rate, the apparent viscosity values of the samples decreased, demonstrating thixotrophy (shear thinning) in both periods. All examples are pseudoplastic flow and thixotropic (shear thinning) in flow behavior. The n values of the samples with biological sludges are higher than the chemical sludges. Rheological behavior of BTS samples showed more tixotropic behavior compare to CTSs.

In general, the increase in solids concentration means an increase in the *k* value, which is the viscosity coefficient. On the contrary, the increase in the consistency index means a decrease for the flow behavior index. In addition, the sludge flow index value is less than 1 of all sludge samples confirms that the treatment sludge exhibits non-Newtonian and pseudoplastic behavior. Results of the study are compatible with the results available in the literature [2, 36]. The seasonal variation of rheological data is also observed when model parameters are compared for October and February.

IV. CONCLUSIONS

In a central IZWWTP, where the wastewater of seasonally operated factories is treated, the properties of the sludge is also changing. The increase in sludge viscosity can be caused clogging in the sludge lines or pump failures. In this study, changes in seasonal viscosity values were investigated for the solution of sludge operation problems. Some physical, chemical and rheological properties of chemical treatment and biological treatment process sludges in two different seasons were determined. The results obtained are given below:

- Both chemical and biological sludge samples showed non-Newtonian pseudoplastic flow behavior.
- When the apparent viscosity values of the sludge samples at a constant shear rate were compared, the increasing solids concentration seemed to cause the initial viscosity values to be higher.
- According to the models used, flow behavior index (n) was found to be less than 1 for all sludge samples. k value, which is the viscosity coefficient, is increased with the increase in the solids concentration and the flow behavior index decreased. Ostwald model's suitability to experimental rheograms is quite high.
- Factories that operate seasonally such as fruit processing facilities must establish a wastewater pre-treatment facility and operate efficiently before discharging wastewater to common sewer line. Thus, viscosity increases of wastewater treatment plant sludge samples can be somewhat prevented.
- Treatment sludge must be controlled to operate wastewater treatment plants efficiently. In operating periods when viscosity increases, alternative coagulants such as PAC may be preferred instead of $FeCl_3$.
- Sludge pumps within the facility should be selected according to the rheological properties of the treatment sludge. The results of the study can be used as sample data for the selection of sludge pumps according to their viscosity ranges during the design phase of similar wastewater treatment plants.

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