Supplementary In-Depth Analysis of the Waste Activated Sludge Dewatering Process Using a Rheological Analysis

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1. INTRODUCTION

The management of sewage sludge has become a challenging issue of growing importance due to urbanization.1−4 As a hydrophilic substance, sewage sludge typically contains 97−98% water, which is difficult to remove.5,6 Dewatering of the sludge to achieve a high proportion of dry solid content is crucial to the operation of municipal sewage treatment plants.7−10 Moreover, the management costs associated with sewage sludge account for approximately 40−50% of the total operational costs of wastewater treatment plants.11,12 Therefore, the management of sewage sludge has caused extensive concern to both society and scientists.13

In the past few decades, efforts have focused on improving the dewatering performance and the dewatering process using conditioning methods,14,15 operational methods,11,16 and process mechanisms.17,18 In these studies, two key issues have been addressed:

- The difficulty of dewatering sewage sludge
- Why suitable chemical conditioning can improve sludge dewaterability.

The topic has been of broad interest in academic research and industry.17 Previous studies have shown that the presence of significant quantities of extracellular polymeric substances (EPS) have high correlations with sludge dewaterability. Therefore, for the key issue above, much attention has been focused on the properties of EPS, including the contents, molecular weight, chemical components, functional groups, and spectral characteristics.8,19−21 However, since the relevant information on EPS is significantly affected by the extraction method, the quantification of the main compounds of EPS often shows great variability and it is difficult to characterize the components of EPS quantitatively.21−23 Meanwhile, no standard EPS extraction procedures and the insufficient

ABSTRACT: Much research has been conducted to improve sludge dewaterability and reveal its dewatering process. However, to date, two key issues remain unsolved: (1) the difficulty of dewatering sludge and (2) why suitable chemical conditioning can improve sludge dewaterability. This study is focused on addressing these two problems using a rheological analysis. Flow and dynamic measurements were performed to investigate the rheological properties of three types of sludge samples (raw sludge, acid-conditioned sludge, and Fenton-conditioned sludge) with different dewatering performances and a total solid content (TS) range of 20−62 g/L (2−6.2 wt %). The measured data were fitted to predict the rheological behaviors of the sludge at moderate and high TS values (15−50 wt %). A horizontal analysis and comparison of the rheological characteristics of the sludge samples indicated that rheological properties of the sludge exhibited a strong dependence on the solids content of the raw and treated sludge. An increase in the solids content significantly strengthened the solid-like properties and increased the deformation resistance, causing the sludge to become more resistant to flow and resulting in lower flowability of the sludge system; this provided an explanation for the difficulty in sludge dewatering. A vertical comparison and analysis of the rheological behavior of the sludge samples addressed the second key issue and indicated that a suitable conditioning method such as acid and Fenton oxidation conditioning had positive effects on the evolution of the rheological parameters of the sludge; namely, the conditioning resulted in weaker viscoelastic properties and better flowability. These results provide insights into the fundamental mechanism of sludge dewatering through rheological analysis.

KEYWORDS: sludge dewatering, rheological analysis, solid contents (TS), flowability, deformation resistance

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knowledge on EPS render the interpretation and comparison of published results difficult. 3, 24 Therefore, it is necessary to develop a complementary perspective beyond EPS.

It is well-known that rheology study being of great importance for characterizing hydrodynamic properties of sludge and a rheological analysis has been proven to be of fundamental importance in sludge characterization. 25 To date, many researchers have tried to apply rheological measurements to predict, control, and optimize the conditioning and dewatering processes. 25–27 For example, the methods of limiting viscosity, yield stress, and peak torque have been successful in the sludge dewatering process. 28-29 Therefore, it is of great importance to address the two key issues from a rheological supplementary perspective. In sludge dewatering process, along with the remove of moisture within sludge, the total solids content (TS) undergoes constant changes. So, it is imperative to measure the rheological properties of sludge systems with different TS for longitudinal comparison. However, the literature has widely focused on the rheological properties of sludge at only one or few values of TS and few studies were conducted on the dewatering process for a wide range of TS values due to the difficulties of obtaining measurements. 29, 30 Generally, these results just reflect the structure changes of the sludge system around its initial TS during pretreatments, the messages which track the rheological properties of sludge with different pretreatments during different mechanical dewatering processes are still limited.

Therefore, the design and the implement of this work was mainly focused into the relationships between sludge dewatering and rheological properties of different chemical pretreatments within a wide TS range. So, we measured the basic rheological properties of three sludge systems (raw sludge, acid-conditioned sludge, and Fenton-treated sludge) with different dewatering performances with a TS range of 20–62 g/L. Then the experiment data were fitted by Origin software to predict the rheological properties of the sludge samples at moderate and high solid contents. The first key research issue was addressed by conducting a horizontal analysis and comparison of the rheological properties of a single sludge system with different TS values. The second key research issue was investigated by performing a vertical comparative analysis of the rheological properties of different sludge systems with the same TS value. The investigation of these two key issues from a rheological perspective provides results that enrich our fundamental understanding of the sludge dewatering process.

2. MATERIALS AND METHODS

2.1. Raw Sludge and Chemicals. The raw sludge (RS) was sampled from the secondary sedimentation tank of the Wangtang municipal wastewater treatment plant (Hefei, Anhui province, China); the plant has a treatment capacity of 180 000 m$^3$/d for the oxidation ditch process. Prior to use, all sludge water was tested on the basis of the centrifugation method (Model 319; Trion, UK) and the measurements were conducted three times at 25 °C. During pretreatments, the messages which track the rheological properties of sludge around its initial TS was measured by Buchner funnel filtration at 0.05 MPa with a filter paper (Whatman No. 1) and by the centrifugation method at 8000 g for different durations; triplicates were performed for all tests. The content of bound water was tested on the basis of the centrifugation method described by Jin et al. 33 A 30 mL sludge sample was centrifuged at 4000g for a certain time, and the water content of the sludge before centrifugation was defined as the total water content (W$_0$). Subsequently, the supernatant was removed and the water content of the centrifuged sludge was defined as the bound water content (W$_b$). The ratio W$_b$/W$_0$ was used to reflect the change in the bound water content of the sludge. 34

2.2. Sludge Conditioning and Dewatering. As shown in Table 2, three types of sludge samples that were treated with methods reported in the literature were chosen: RS, acid-

### Table 1. Characteristics of the Raw Sludge (RS)

| symbol | conditioners | pH  | Fe$^{2+}$ | H$_2$O$_2$ | conditioning procedures |
|--------|--------------|-----|-----------|-------------|-------------------------|
| RS     | none         | 6.79| 0         | 0           | 300 rpm/3 min            |
| pH = 3 | H$^+$        | 3.00| 0         | 0           | 300 rpm/3 min            |
| Fenton | Fe$^{2+}$/H$_2$O$_2$ | 2.80| 14.30     | 25.87       | Fe$^{2+}$ solutions → 150 rpm/5 min → H$_2$O$_2$ → 100 rpm/30 min |

### Table 2. Different Conditioning Procedures for Sludge

| symbol | conditioners | dosage (mg/g TS) |
|--------|--------------|------------------|
| RS     | none         | H$^+$ solutions  |
| pH = 3 | H$^+$        | 300 rpm/3 min    |
| Fenton | Fe$^{2+}$/H$_2$O$_2$ | 150 rpm/5 min → H$_2$O$_2$ → 100 rpm/30 min |

conditioned sludge, and Fenton reagent-conditioned sludge. The RS was used as the control and was stirred at 300 rpm for 3 min; the acid-conditioned sludge and Fenton reagent-conditioned sludge were the experimental treatments. For the acid-conditioned sludge, the pH was adjusted to 3 (denoted as pH = 3) using H$_2$SO$_4$ (1 M) as a conditioner; it was stirred at 300 rpm for 3 min; the Fenton reagent-conditioned sludge was denoted as Fenton and the dosage of Fenton’s reagent was based on the study of Yu et al. 33 For acid and Fenton conditioned sludges, its pH did not adjust back to 7 throughout the measurement. The conditioning producers for different types of sludge are shown in Table 2. The TS value of raw sludge was 20.85 g/L, then we gently thickened the raw sludge, acid-conditioned (pH = 3), and Fenton-conditioned sludge by centrifugation and then removed the certain supernatant to achieve high TS values samples. The sludge samples were thickened using centrifugation at 2000g for 10 min to remove the supernatant and to achieve a TS range of 20–62 g/L.

After conditioning, the dewatering performance was estimated by determining the capillary suction time (CST), the moisture content of the dewatered cake, and the content of bound water. The CST values were obtained with a CST instrument (Model 319; Trion, UK) and the measurements were conducted three times at 25 °C. The moisture of the dewatered sludge was measured by Buchner funnel filtration at 0.05 MPa with a filter paper (Whatman No. 1) and by the centrifugation method at 8000 g for different durations; triplicates were performed for all tests. The content of bound water was tested on the basis of the centrifugation method described by Jin et al. 33 A 30 mL sludge sample was centrifuged at 4000g for a certain time, and the water content of the sludge before centrifugation was defined as the total water content (W$_0$). Subsequently, the supernatant was removed and the water content of the centrifuged sludge was defined as the bound water content (W$_b$). The ratio W$_b$/W$_0$ was used to reflect the change in the bound water content of the sludge. 34

### 2.3. Rheometric Technique. A rotational AR-2000ex rheometer (TA Instruments, New Castle, DE, USA) equipped with a cup and bob geometry (29 mm inner diameter, 32 mm outer diameter, 44 mm length) was used to measure the
impacts of the solid contents and conditioning processes on the rheological properties of sludge. The sludge was first presheared at a shear rate of 500 s⁻¹ for 5 min and then left at rest for 10 min to ensure reproducible results.35,36 Both dynamic and steady tests were carried out to analyze the rheological behavior of sludge samples.

It has been demonstrated that a dynamic rheological test can provide information on the viscoelastic and viscoplastic characteristics of sludge. In this study, shear strain tests (0.01–200%) were carried out at a constant frequency (1 Hz) and temperature (25 °C) to determine the structural properties of sludge and its linear viscoelastic regions.37,38 Dynamic and steady tests were carried out to analyze the rheological behavior of sludge samples.

Flow measurements were conducted as the shear rate increased logarithmically from 0.01 to 500 s⁻¹ for 10 min in the steady shear mode to determine the viscosity properties of the sludge. All rheological tests were conducted twice. Meanwhile, the Herschel–Bulkley model (eq 1) was used to fit the rheological data, which can efficiently describe the rheological properties of sludge:

\[ \tau = \tau_y + k \cdot \gamma^n \]  

(1)

where \( \tau \) is the shear stress (Pa), \( \tau_y \) is the yield stress (Pa), \( k \) is the fluid consistency index (Pa·sⁿ), and \( n \) is the flow index (dimensionless).

3. RESULTS AND DISCUSSION

3.1. Sludge Dewatering Performance. The reduction in the bound water content is commonly used as a critical parameter to predict the dewatering efficiency of pretreatments during sludge dewatering.13 Figure 1a shows the relationship between the bound water content in the RS and the centrifugation time at 4000g. It was shown that the amount of bound water (\( W_b/W_i \)) decreased from 19.25 ± 0.30% to 13.66 ± 0.21% as the centrifugation time increased from 1 to 12 min but the rate of decrease in the bound water slowed down with increasing centrifugation time. For example, at a centrifugation time of 30 min, the amount of bound water (\( W_b/W_i \)) was only reduced to 12.54 ± 0.04%, representing a decrease of only 8.20% compared with the amount of bound water at 13 min of centrifugation time. These results suggested that the conventional mechanical dewatering operation did not efficiently reduce the amount of bound water in the RS, limiting the effectiveness of the sludge dewatering performance. For example, for the sludge dewatered by the centrifugation method, the moisture content of the sludge cake only slightly decreased from 90.05 ± 0.14% to 85.53 ± 0.06% as the centrifugation time increased from 1 to 30 min (Figure 1b). Generally, 30 min of centrifugation represents the limit in terms of dewatering of the sludge and the moisture content of the sludge remained high, suggesting that the dewatering performance of the mechanical operation is poor, which is consistent with the first key issue. A similar trend (Figure 1b) was also observed for the sludge dewatered by another common mechanical dewatering method, i.e., the Buchner funnel filtration.23

However, the dewatering performance of the sludge was significantly improved by chemical pretreatments, such as acid conditioning and the Fenton process (Figure 2). For example, the CST of the RS was 71.9 ± 0.8 s, but it was significantly lower for the acid-conditioned sludge (39.2 ± 0.8 s) and the Fenton oxidation conditioned sludge (20.9 ± 1.2 s). These results showed that the two chemical pretreatments significantly improved the filtration performance of the sludge. For the 5 min filtration, the moisture content was 81.81 ± 0.38% for the RS, 72.14 ± 0.20% for acid conditioning, and 70.09 ± 0.38% for the Fenton oxidation. For the 20 min filtration, the moisture content was 75.33 ± 0.64% for the RS, whereas the value was significantly lower for acid conditioning (68.01 ± 0.41%) and Fenton oxidation (65.14 ± 0.98%). These results indicated the importance of appropriate pretreatments for sludge dewatering.

3.2. Effects of TS on the Rheological Properties. Flow measurements and dynamic measurements are the two common tests used to obtain information on the internal...
structure of the sludge suspension. Flow and dynamic rheometry were chosen for the rheological characterization of the three types of sludge systems.

3.2.1. Flow Measurements. Flow measurements provide message on the viscosity properties of material suspension. \(^4\) The flow curves of the RS and pretreated sludges in the range of 0.1 to 500 \(s^{-1}\) is presented in Figure 3. Both the raw and pretreated sludge samples exhibited non-Newtonian characteristics and shear-thinning behavior. The acid and Fenton oxidation pretreatments were effective in reducing the non-Newtonian fluid characteristics of the sludge system. In particular, the shear stress and apparent viscosity of the pretreated sludge were lower than that of the RS at all shear rates and the Fenton oxidation treatment resulted in the lowest values.

The Herschel–Bulkley model with the additional yield stress \((\tau_y)\) parameter was used to determine the differences between the raw and treated sludge samples and evaluate the non-Newtonian characteristics. \(^36\) The yield stress \((\tau_y)\) and the consistency index \((k)\) of all three sludge sample increased exponentially with an increase in the TS value (Figure 4). When the TS value increased from 20.85 g/L to 62.08 g/L, the yield stress \((\tau_y)\) and the consistency index \((k)\) of the RS globally increased from 0.21 Pa to 0.40 to 19 Pa \((R^2 = 0.999)\) and 13.81 \((R^2 = 0.999)\), respectively, however, the flow index \((n)\) decreased significantly from 0.493 to 0.311 \((R^2 = 0.981)\). The relationships between the key rheological parameters and the TS values were similar for the acid and Fenton oxidation pretreated sludge samples. These results indicated that the non-Newtonian flow characteristics of sludge were strengthened at higher TS values. \(^37\) The evolution of the apparent viscosity (at constant shear rates of 10, 100, and 500 \(s^{-1}\)) as a function of the TS value of the sludge samples is shown in Figure 5. In all samples, the apparent viscosity increased exponentially as the TS values increased. In fact, Baudez et al. \(^41\) demonstrated that an increase in the solid content can strengthen the hydrodynamic interactions (between the solid particles and surrounding particles) and the nonhydrodynamic interactions (between the solid particles) and the yield stress and apparent viscosity reflected these interactions. Therefore, our results suggested that the higher the TS value, the lower the flowability and the more viscous the fluid, which is undesirable for dewatering. This implies that a dewatering process in which greater amounts of water are removed from the sewage sludge could significantly strengthen the inner structure and the non-Newtonian flow properties of the sludge system and would hinder the dewatering performance, especially if deep dewatering is desired.

We also conducted a vertical comparison and analysis of the effect of the TS values on the rheological properties of the three types of sludge. For the sludge with the same solid content, it was found that both the non-Newtonian flow properties of sludge and the flow resistance were notably weakened after the sludge was pretreated with acid or Fenton oxidation, suggesting that the internal structure of the treated sludge was damaged. As shown in Figure 4, with the same solid content of 62.08 g/L, the yield stress \((\tau_y)\) and \(k\) decreased from 19 Pa and 13.81 to 8 Pa and 4.7, respectively, after the sludge was pretreated with acid and the values were lower for the Fenton oxidation treated sludge at 5 Pa and 3.23. In contrast, the flow index \((n)\) was 0.311 for the RS, 0.40 for the acid-pretreated sludge, and 0.41 for the Fenton oxidation-treated sludge. These results clearly indicated that the chemically conditioned sludge was much closer to the Newtonian fluid. \(^35\) The acid and Fenton oxidation pretreatment significantly decreased the flow resistance of the sludge and improved the flowability of the sludge system. Therefore, the apparent viscosity of the treated sludge subject to mechanical stress was significantly lower (Figure 5). The apparent viscosity of the RS at a solid content of 62.08 g/L and a shear rate of 500 \(s^{-1}\) was

![Figure 3](https://dx.doi.org/10.1021/acsestengg.0c00126)  
**Figure 3.** Flow curves of the RS and treated sludge (TS = 20.85 g/L) obtained at 25 °C: solid triangles, shear stress; solid circles, viscosity.

![Figure 4](https://dx.doi.org/10.1021/acsestengg.0c00126)  
**Figure 4.** Relationships between the rheological parameters and the solids content of the raw and treated sludge samples at 25 °C.
0.21 Pa·s, whereas the values for the acid and Fenton oxidation treatments were 0.15 and 0.11 Pa·s, respectively, representing a decrease by 28.61% and 47.60%. The decrease in the yield stress ($\tau_y$) and the consistency index ($k$) and the increase in the flow index ($n$) suggested that the non-Newtonian flow characteristics and the strength of the inner structure of the treated sludge were weakened. On the basis of these results and previous studies, we believe that the acid or advanced oxidation treatment destroyed the structure of the sludge flocs, causing the degradation of large amounts of EPS and intracellular polymers and their release into the liquid. Previous studies have shown that both acid and oxidation pretreatments can increase the free water content and efficiently weaken the network strength of sludge, which could reduce the flow resistance of the sludge system under external deformation and provide effective dewatering.

3.2.2. Dynamic Measurements. Dynamic measurements provide information on the viscoelastic and viscoplastic properties of sludge. The evolution of the strain dependence of the storage and loss modulus under a constant frequency (1 Hz) for both raw and treated sludge samples at different solid contents is shown in Figure 6. The storage modulus $G'$ and loss modulus $G''$ were nearly constant at a low strain, suggesting a linear viscoelastic regime. Consistent with what is usually observed in sludge suspensions, the values of $G'$ and $G''$ increased with the increase in the solid contents for all three types of sludge, indicating that the solid content has a large impact on the viscoelastic characteristic of the sludge. The higher the solid content, the stronger the network strength is and the larger the colloidal forces of the sludge flocs are.

A comparison of the effect of the TS values on the viscoelastic properties of the different sludge types indicated that an increase in the TS content significantly increased the complex modulus ($G^*$) value and the solid-like properties. As shown in Figure 7a, when the TS value increased from 20.85 to 62.08 g/L, the complex modulus ($G^*$) value of the RS increased significantly from 8.63 to 408 Pa, whereas the value of tan($\delta$) decreased from 0.1002 to 0.074, indicating that the viscoelasticity of the concentrated sludge increased markedly. The evolution of the complex modulus ($G^*$) and tan ($\delta$) for different solid contents were similar for the acid- and Fenton oxidation-treated sludge samples. It is well-known that a high value of $G^*$ indicates a strong ability to resist deformation. The increase in the value of $G^*$ with increasing solid content provides evidence that the ability to resist deformation is strengthened with increasing solid content. In addition, the increase in the solid content also weakened the liquid-like properties of the sludge. These changes imply that the viscoelastic properties of the sludge were strengthened as the solid content increased. Furthermore, the dynamic yield stress $\tau_{c, dyn}$ corresponding to the end of the linear viscoelastic region is the product between $G^*$ on the plateau and the critical shear strain, increased with increasing solid content, whereas the
critical shear strain $\gamma_c$ representing the linear viscoelastic region exhibited an opposite response. As shown in Figure 7b, the $\tau_{c, dyn}$ increase with SS content following a power law. For example, when the TS value increased from 20.85 to 62.08 g/L, the value of $\tau_{c, dyn}$ of the RS increased from 4.47 to 97.80 Pa. The responses were similar for the acid- and Fenton oxidation-treated sludge, suggesting that an increase in the solid content improved the internal interactions of the flocs to consolidate the structure; this result is consistent with the changes in the yield stress obtained from the flow measurements. Notably, the response of the critical shear strain $\gamma_c$, which indicates the linear viscoelastic region, was opposite to results reported in previous studies. For example, as the solid content of the RS increased from 20.85 to 62.08 g/L, the value of $\gamma_c$ decreased significantly from 51.75% to 24.00% and the responses were similar for the acid- and Fenton oxidation-treated sludge. In fact, some researchers found that the value of $\gamma_c$ increased with increasing solid content, whereas other authors reported that the value of $\gamma_c$ was not dependent on the solid content. The different $\gamma_c$ results for sludge with different solid contents may be attributed to the origin of the sludge sample, implying that the use of the parameter $\gamma_c$ for investigating the impact of the solid content on the viscoelasticity of sludge may not appropriate and may provide misleading information.

The results shown in Figure 7 indicate that an increase in the solid content strengthens the solid-like properties. Therefore, the sludge system needs to be subjected to a stronger external mechanical force to cause deformation between the solid and liquid phases in a highly concentrated sludge system.

A vertical comparison of the effects of the TS values on the viscoelastic properties of the three types of sludge samples was also conducted. As shown in Figure 7a, for the sludge at the same TS value of 62.08 g/L, the value of $G^*$ decreased from 408 Pa for the RS to 314 Pa for the acid-treated sludge and to 233 Pa for the Fenton oxidation treated-sludge, representing a decrease by 23.04% and 42.90%, respectively. The values of $\tan(\delta)$ increased from 0.074 for the RS to 0.094 for the acid-treated sludge and to 0.105 for the Fenton oxidation-treated sludge, representing an increase of 27.03% and 41.90%, respectively. These changes imply that the viscoelastic properties were significantly lower and the liquid-like properties were higher in the treated sludge. Consequently, the treated sludge is easily deformed under external stress. Furthermore, the values of $\tau_{c,dyn}$ and $\gamma_c$ were significantly lower in the treated sludge, implying that the network strength and colloidal forces were weakened in the treated sludge. The three types of sludge exhibited similar trends for these parameters at other solid contents. The dynamic measurement results imply that suitable conditioning, especially chemical conditioning, significantly weakened the solid-like properties of the sludge in the linear viscoelastic region, which is desirable for dewatering.

The flow and dynamic measurement results of the sludge samples provide important information on the two key research topics of this study; however, due to limitations of the used geometries, the range of measured TS values was still relatively small. When the TS content increases, dominating interactions of sludge transferred from a lubricated regime (indirect contacts) to a frictional regime (direct contact), leading to dilatancy and fractures. Although Mouzaoui, Baudez, Sauceau, and Arlabosse conducted a work aiming to develop experimental rheological procedure adapted to dewatered sludge up to 45% (TS%), it is still debatable to put it in practice. Meanwhile, though the model data fitted with limited TS range (20–62 g), the measured data in the limited range shows close correlations of these variations. To obtain additional insight, the experiment data was fitted by Origin software and used to predict the rheological properties of the sludge samples at moderate and high solid contents. This provides insights into the two key issues for an expanded range of TS values.

3.3. Rheological Simulation and Prediction. Figure 8 illustrates the prediction results of the flow yield stress $\tau_{c, dyn}$ and the high-shear viscosity $n_\alpha = 500$ s$^{-1}$ of these sludge samples at different TS values. It was observed that both $\tau_{c, dyn}$ and $n_\alpha$ exponentially increased with the increase of solid content. For example, as the TS value of the sludge increased from 15% to 30%, the minimum stress required to induce a continuous flow was 15.71 times higher; the value of $n_\alpha$ which reflects the hydrodynamic interactions of the sludge during steady flow, increased 7.95 times. These results match those of previous studies that smaller considerations of sludge can potentially increase the filtration kinetic, which is not favorable for deep sludge dewatering. However, the acid conditioning and Fenton oxidation treatments markedly lower the mechanical force required to change the hydrodynamic behavior and flowability of the sludge system. For example, as the TS value of the sludge increased to 30%, the $\tau_{c, dyn}$ and $n_\alpha$ values of the acid-conditioned sludge and those of the Fenton oxidation-treated sludge represent decreases of 68.08% and 84.82% and 10.42% and 36.98%, respectively, compared to the RS. Therefore, the treated sludge, especially the Fenton oxidation-treated sludge had better flowability and phase transformation occurred more likely, which enabled the separation of the solid and liquid phase of the sludge system. The prediction results for the sludge at moderate and high
solid contents were consistent with the flow measurement results at low solid content.

The fitted predictions of the complex modulus \( G^* \) of the three types of sludge at different solid contents are presented in Figure 9. We observed that the value of \( G^* \) exhibited a power-law increase with increasing solid content. For example, as the TS value increased from 15% to 30%, the \( G^* \) value of the RS representing an increase of 12.80 times. However, acid conditioning and Fenton oxidation conditioning significantly weakened the deformation resistance of the sludge. For example, at a solid content of 30%, the \( G^* \) of the acid-treated sludge and that of the Fenton oxidation-treated sludge representing decreases of 23.13% and 80.25%, respectively, compared to the RS.

In summary, the simulation results were consistent with the measured results in the flow and dynamic tests, indicating that the prediction results can provide insights into the two key issues for an expanded range of TS values. Compared with the study of sludge EPS, using rheological analysis can provide a new perspective to reveal the hydrodynamic of solid–liquid separation for the sludge dewatering process, which enables the fundamental understanding of sludge management. In fact, previous studies have noted that the rheological properties of sludge correlate well with the quantities of EPS and physicochemical properties of sludge;\(^{42,50}\) it would be interesting to explore the usage of rheological analysis to unravel the dewatering mechanism and optimize the conditioning process in the future.

4. CONCLUSIONS

In this study, we conducted an in-depth analysis of the rheological properties of three types of sludge with different dewatering performances at different solid contents. The main conclusions were as follows:

- An increase in the solid content significantly strengthened the solid-like properties and increased the deformation resistance of the sludge, causing it to become more resistant to flow and resulting in lower flowability. The rheological behavior limited the effectiveness of the dewatering performance.
- Suitable conditioning methods such as acid and Fenton oxidation conditioning had positive effects on the evolution of the rheological parameters of sludge and resulted in weaker viscoelastic and non-Newtonian properties and better flowability of the treated sludge. As a result, the dewatering performance was better for the acid- and Fenton oxidation-treated sludge.
- The rheological analysis extended our knowledge of key issues of interest in sludge dewatering research and provided a deeper insight into the fundamental mechanisms of the sludge dewatering process.

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Figure 8. Relationship between the solids content and the predicted values of (a) flow yield stress and (b) high-shear (500 s\(^{-1}\)) viscosity for the RS and treated sludges.

Figure 9. Relationship between the solids content and the predicted values of the complex modulus (\( G^* \)) for the RS and treated sludges.
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