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Thermally Modified Drinking-Water Sludge as a Mineral Conditioner for Municipal Sludge Dewatering and Low-Temperature Drying

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Abstract

Sludge-conditioning strategies are commonly optimized for filtration performance, with less attention paid to the rheological and textural properties of concentrated sludge and their relevance to low-temperature drying. Here, thermally modified drinking-water sludge (HDWS) was evaluated as a waste-derived mineral conditioner for filtration dewatering and low-temperature drying. The specific resistance to filtration (SRF) was lowest at 30% DS, whereas the 60% DS treatment reduced the moisture content to 35.66% after drying at 60 °C for 30 min, indicating that the optimum filtration condition did not deliver the best drying performance. Increasing the HDWS dosage from 0 to 60% DS reduced the Jenike shear stress from approximately 565 to 490 Pa and the apparent yield stress from approximately 670 to 380 Pa, while also decreasing adhesiveness and cohesiveness. At higher dosages, the sludge retained relatively high small-strain stiffness but exhibited lower nonlinear elastic and viscous resistance. These responses were consistent with weakened macroscopic bonding and altered deformation-dependent energy dissipation after HDWS addition. A possible contribution from mineral-particle contacts is suggested, although the underlying microstructural mechanism was not directly resolved. The 60% DS treatment shortened the time required to reach 20% water content to approximately two-thirds of that for raw sludge but reduced the cake calorific value from approximately 9.6 to 4.3 kJ g⁻¹. HDWS, therefore, exhibited process-specific trade-offs, and its dosage should be selected according to the targeted unit operation and downstream management route rather than regarded as a single overall optimum.

Keywords: drinking water sludge; sticky phase; nonlinear rheology; sludge dewatering; low-temperature drying

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1. Introduction

Sludge management is a critical component of pollution mitigation, carbon management, and resource recovery in wastewater treatment systems [1]. Reducing the water content of municipal sludge through deep dewatering is essential for sludge volume reduction and for improving the feasibility of subsequent resource recovery and disposal

[2]. Deep dewatering commonly involves sequential mechanical dewatering and thermal drying [3,4]. Mechanical processes rapidly remove most of the readily separable water, whereas low-temperature drying further reduces cake water content and improves its suitability for incineration, construction material production, or other co-treatment routes [5,6]. In practice, however, mechanically dewatered sludge cakes often retain a relatively high water content and exhibit pronounced adhesiveness, cohesiveness, and plastic deformation [7,8]. These properties restrict heat and mass transfer during subsequent drying, prolong the drying period, and increase energy demand [1]. Improving the structural state of mechanically dewatered cakes through upstream conditioning may, therefore, provide an effective means of enhancing downstream low-temperature drying.

Most sludge-conditioning studies have focused on the mechanical filtration stage, with capillary suction time (CST), specific resistance to filtration (SRF), and cake water content commonly used as the principal performance indicators [2,5]. Iron- and aluminum-based coagulants and polyacrylamide improve filtration by charge neutralization, floc restructuring, and particle aggregation [9], whereas oxidative conditioning using Fenton reagents, persulfate, or ferrate is generally designed to disrupt extracellular polymeric substances (EPSs), transform organic constituents, and redistribute water within sludge flocs [2,10–12]. Although these approaches can improve filtration behavior, their evaluation commonly ends at the filtration or mechanical-dewatering stage [5,13]. Consequently, much less is known about how the conditioned cake responds when subsequently subjected to low-temperature drying [6,14,15]. Skeleton-building materials, including fly ash, biochar, red mud, phosphogypsum, and sludge-derived char, have recently attracted attention because rigid particulate inclusions can reduce cake compressibility, preserve water transport pathways, and improve deep dewatering performance [16–18]. Nevertheless, most studies of skeleton-assisted conditioning have also been confined to mechanical filtration [19]. Whether a cake exhibiting improved filtration performance necessarily retains favorable transport and handling properties during low-temperature drying remains unresolved.

Studies of sludge rheology and the sticky phase encountered during drying provide a basis for addressing this question [20]. Wang et al. used rheological measurements to elucidate the effects of acid conditioning on activated-sludge dewatering, demonstrating a close association between sludge structural stability, yielding behavior, and solid–liquid separation [21]. Liang et al. developed a uniaxial cyclic compression method for mechanically dewatered sludge and showed that concentrated sludge cakes undergo complex and partly irreversible viscoelastic–plastic deformation under loading [7]. Mouzaoui et al. subsequently established a rheological procedure applicable to pasty sludge containing up to 45% dry matter, confirming that mechanically dewatered cake cannot be adequately represented as a low-solids suspension [8]. From the perspective of drying, Peeters et al. systematically characterized the sludge sticky phase and showed that sludge can become strongly adhesive and difficult to handle over an intermediate range of solids contents [22,23]; these adverse properties can be mitigated through inorganic conditioning. Collectively, these findings indicate that the constraints on sludge volume reduction extend beyond early-stage filtration and persist as mechanically dewatered cakes pass through a viscoplastic regime, which may include a pronounced sticky phase, during their transition towards a low-moisture solid [5,8,24]. The performance of a conditioner should, therefore, not be judged solely from the CST or SRF, but also from its capacity to reduce cake adhesiveness, cohesion, and nonlinear rheological resistance, thereby facilitating moisture transport during subsequent drying.

Drinking water sludge (DWS) represents a practically available material for developing such an integrated conditioning strategy [25]. Depending on the source water and co-

agulant used, DWS commonly contains abundant Si-, Al-, and/or Fe-bearing phases together with residual metal-coagulant precipitates [1,26]. Consequently, it has been investigated for sewage sludge dewatering, phosphorus removal, sulfide control, adsorbent production, and construction material applications [25,27]. Li et al. reported that alum sludge improved sewage sludge dewatering through the combined effects of charge neutralization, adsorption and bridging, and inorganic skeleton formation, while reducing the demand for polyacrylamide [25]. Rebosura et al. showed that iron-rich DWS could be dosed into sewer systems to suppress sulfide while providing downstream benefits for phosphorus control [26]. More recently, Xiao et al. demonstrated that heated DWS, used as part of a skeleton-building and ozone-catalytic conditioning strategy, could enhance waste-activated sludge dewaterability, highlighting the potential for coordinated management of drinking water and wastewater sludges [28]. These studies establish DWS as a functional residual rather than an inert waste, with potential contributions from inorganic skeleton formation, metal-mediated reactivity, and interfacial regulation. However, it remains unclear how thermally modified DWS affects the viscoplastic behavior and textural-mechanical properties of mechanically dewatered sludge and whether these changes translate into improved low-temperature drying. Previous studies have focused primarily on the filtration dewaterability of DWS-conditioned sludge or have incorporated thermally modified drinking water sludge (HDWS) into combined oxidation and skeleton-building treatments [25,28]. In contrast, the present study evaluates HDWS as a standalone mineral conditioner and compares its effects across filtration, nonlinear rheology, texture and low-temperature drying, thereby identifying process-specific dosage responses across these endpoints.

In this study, thermally modified drinking water sludge (HDWS) was used as a sludge-derived conditioning amendment designed to improve not only mechanical dewatering but also subsequent low-temperature drying. Changes in the inorganic composition and particle structure of DWS induced by thermal modification were first characterized. The effects of HDWS dosage on the mechanical dewaterability, nonlinear rheological response, textural and mechanical properties, and low-temperature drying behavior of municipal sludge were then systematically evaluated. We specifically tested whether HDWS could alter the structural state of mechanically dewatered cakes by diluting the compressible organic solids fraction, providing particulate skeleton support, and reducing the resistance associated with viscoplastic deformation, thereby shortening the drying time and reducing the energy required to reach a target water content. This work extends the evaluation of sludge conditioning from filtration-centered indices to the integrated performance of the mechanical-dewatering–low-temperature-drying sequence and explores a sludge-to-sludge route for the coordinated management of drinking water and municipal wastewater residuals.

2. Materials and Methods

2.1. Sludge Samples and Preparation of HDWS

Raw municipal sludge (RS) was collected from the thickening tank of the Yangli Wastewater Treatment Plant in Fujian, China. After collection, the sludge was passed through a 100-mesh stainless-steel sieve to remove coarse impurities, stored at 4 °C, and used within one week [29]. The physicochemical characteristics of the RS are summarized in Table 1. The D_{50} value of 34.24 μm characterizes the initial floc-size scale of the RS, which is relevant because floc size influences cake packing and drainage resistance during mechanical dewatering. Drinking water sludge (DWS) was collected as a mechanically dewatered cake from the Fuzhou Western District Drinking Water Treatment Plant in Fujian, China. The plant uses the Min River as its source water and polyaluminium chloride (PAC) as the primary coagulant. The as-received DWS had a water content of 46.26%.

After collection, the DWS was air-dried, ground, and heated in a muffle furnace at 800 °C for 2 h. The resulting material was allowed to cool to room temperature and then passed through a 50-mesh sieve to obtain thermally modified drinking water sludge (HDWS).

Table 1. Basic characteristics of sludge.

Parameter	Measured Value
Water Content (%)	96.42 ± 0.81
pH	6.89 ± 0.95
Zeta Potential (mV)	−22.76 ± 1.27
Capillary Suction Time (CST, s)	264.20 ± 1.90
Sludge Solid Content (SS, g/L)	32.23 ± 0.46
Volatile Suspended Solids (VSSs, g/L)	18.04 ± 0.48
D ₅₀ (μm)	34.24 ± 0.58

2.2. HDWS Conditioning, Dewatering, and Low-Temperature Drying

HDWS was added at dosages of 0, 15, 30, and 60% relative to the dry-solids mass of RS, with the 0% treatment serving as the unconditioned control. A predetermined amount of homogenized RS was mixed with the corresponding amount of HDWS at 500 rpm for 5 min to promote contact between the HDWS particles and the sludge flocs, colloidal constituents, and aqueous phase. The selected dosage range was used to examine the effects of different HDWS back-mixing levels on sludge dewatering and the subsequent behavior of the concentrated sludge within the viscoplastic regime. Immediately after conditioning, each sample was divided into separate aliquots for SRF measurement and drying tests. The drying aliquot was centrifuged at 8000 rpm for 20 min and adjusted to approximately 84% water content. Thus, filtration and drying were evaluated separately rather than consecutively using the same cake. Sludge filterability was evaluated using specific resistance to filtration (SRF), measured with a standard SRF apparatus [13]. To prepare cake samples for the drying experiments, the conditioned sludge was initially dewatered by centrifugation at 8000 rpm for 20 min, after which its water content was adjusted to approximately 84%. The pre-dewatered sludge was then formed into circular cakes with a mass of approximately 20 g, a thickness of approximately 5 mm, and a diameter of approximately 7 cm. The prepared cakes were dried using a halogen moisture analyzer at 60 °C under an air atmosphere. The temperature of 60 °C was selected to represent heat-pump-assisted low-temperature drying, for which 50–70 °C is commonly used [15]. The 30 min endpoint was selected as a standardized short-duration comparison reflecting the time constraints of continuous processing; previous work indicates that the initial 30 min spans the transition from coupled heat transfer and diffusion to diffusion-dominated drying [30]. Cake mass and water content were continuously recorded during drying. The drying rate was expressed as a positive value using $R = -(1/m_{DS})(\Delta m_w/\Delta t)$, where m_{DS} and m_w are the dry-solids mass and water mass, respectively. For an approximately 20 g cake with an initial water content of 84%, the initial dry-solids and water masses were approximately 3.2 and 16.8 g, respectively; at 20% water content, the remaining water mass was approximately 0.8 g. Drying performance was evaluated from the water content after 30 min, the drying rate, and the time required to reach a predetermined target water content. These tests were designed to determine how HDWS conditioning affected moisture transport and the low-temperature drying behavior of mechanically dewatered sludge cakes.

2.3. Rheological and Textural Characterization of Sludge in the Viscoplastic Regime

Macroscopic shear resistance was evaluated using a Jenike shear test adapted from the procedure developed by Peeters et al. for characterizing sludge stickiness [22]. Briefly, 15 g of conditioned sludge was uniformly placed in an open steel cylinder (internal diameter: 5.5 cm) resting on a smooth stainless-steel plate and preconsolidated under a normal stress of 9.1 kPa for 1 min. After removal of the consolidating load, the horizontal force was increased quasi-statically until incipient sliding, and the critical force divided by the nominal contact area was reported as the Jenike shear stress. The steady-shear and oscillatory rheological properties of the sludge conditioned with different HDWS dosages were measured using a strain-controlled rotational rheometer (ARES-G2, TA Instruments, New Castle, DE, USA). An 8-mm diameter parallel-plate geometry with a gap of 2 mm was used. Sandpaper was attached to the upper and lower plate surfaces to minimize wall slip, and silicone oil was applied around the sample edge to limit moisture evaporation. Before rheological measurement, all sludge samples were concentrated by centrifugation and adjusted to a water content of 84%. The samples were pre-sheared at 100 s^{-1} for 60 s and allowed to rest for 180 s. Steady-shear tests were performed over a shear-rate range of $0.01\text{--}100\text{ s}^{-1}$ to obtain the relationship between the shear stress and shear rate and to determine the apparent yield stress using the Herschel–Bulkley model [31]. Oscillatory strain amplitude sweeps were conducted at an angular frequency of 5 rad s^{-1} over a strain amplitude range of $0.01\text{--}100\%$, during which the complex modulus (G^*), was recorded as a function of the strain amplitude [21]. Nonlinear viscoelasticity was further analyzed using large-amplitude oscillatory shear (LAOS) stress decomposition. The LAOS tests were conducted at an angular frequency of 5 rad s^{-1} over a strain amplitude range of $1\text{--}100\%$. The within-cycle variations in stress, strain, and strain rate were used to determine the large-strain modulus (G'_L), minimum-strain modulus (G'_M), large-rate dynamic viscosity (η'_L), and minimum-rate dynamic viscosity (η'_M). The G'_L , G'_M , η'_L and η'_M values were extracted at a strain amplitude of 25%. These parameters were used to characterize intracycle strain stiffening or softening and shear thickening or thinning, following the definitions proposed by Ewoldt et al. [32].

The textural properties of the mechanically dewatered sludge cakes were determined using a texture analyzer (CT3-1500, Brookfield, Middleboro, MA, USA) equipped with a P75 cylindrical probe and operated in texture profile analysis mode. Cylindrical specimens with a diameter of 20 mm and a height of 10 mm were prepared for analysis. The pre-test, test, and post-test speeds were set to 1, 3, and 5 mm s^{-1} , respectively. The compression strain and trigger load were set to 50% and 5 g, respectively. Hardness, adhesiveness, and cohesiveness were obtained from the resulting force–time curves [33]. All measurements were performed in triplicate.

2.4. Additional Characterization and Energy Analysis

The surface morphology and microstructure of DWS and HDWS were examined using scanning electron microscopy (GeminiSEM 300, ZEISS, Oberkochen, Germany). The two-dimensional apparent pore size distribution was quantified from SEM micrographs using ImageJ software (Image J version 1.53). After spatial calibration against the SEM scale bar, the images were converted to 8-bit grayscale and segmented using a consistent thresholding procedure, following the image analysis approach described by Ike et al. [34]. Their crystalline phases were characterized using X-ray diffraction (SmartLab 9 kW, Rigaku, Akishima, Japan), and their major inorganic oxide compositions were determined using X-ray fluorescence spectroscopy (ZSX Primus III+, Rigaku, Akishima, Japan). The calorific values of the samples were measured using an automatic calorimeter (ZDHW-8A, Hebi Xintianke Coal Quality Instrument Co., Ltd., Hebi, China). The electricity consumption was estimated from separate oven-drying tests using 2.0 kg sludge batches with

an initial water content of 84%. Each batch contained 0.32 kg of dry solids and 1.68 kg of water and was dried at 60 °C until its total mass decreased to 0.40 kg, corresponding to a 20% water content and 1.60 kg of water removed. The sample mass was monitored using a balance placed inside the oven using an oven-rated power of 1.55 kW. Because electricity was not measured directly, the calculated values represent rated power estimates without blank or standby power correction. These parameters were used to assess the effect of HDWS conditioning on the energy demand of subsequent low-temperature drying. Unless otherwise specified, all experiments were conducted with at least three independent replicates, and the results are presented as the mean $\pm$ standard deviation. Comparisons among treatments were interpreted descriptively without inferential statistical testing.

3. Results and Discussion

3.1. Structural Changes in DWS Induced by Thermal Modification and Their Implications for Dewatering–Drying Performance

The combined XRD and XRF results showed that RS, DWS, and HDWS contained abundant Si-, Al-, and Fe-bearing mineral components (Figure 1 and Table 2). Thermal treatment did not substantially alter the positions of the major diffraction peaks of DWS, although the intensities of several reflections increased. Together with the XRF results, this observation indicates that the dominant crystalline phases were largely retained, whereas the normalized XRF results showed higher relative proportions of the major inorganic oxides in HDWS than in DWS. These results are consistent with previous reports but do not directly quantify organic matter removal or thermal mass yield [27]. The normalized proportions of SiO₂, Al₂O₃, and Fe₂O₃ in HDWS were 58.68%, 25.90%, and 6.49%, respectively, together accounting for 91.07% of the oxide composition detected by XRF. This composition is consistent with previous characterizations of thermally treated drinking water sludge and provides a compositional basis for the use of HDWS as a mineral skeleton amendment [28]. SEM imaging further revealed marked morphological differences between DWS and HDWS. Untreated DWS consisted predominantly of dense, irregular aggregates, whereas HDWS exhibited greater particle fragmentation, a rougher surface, and more open interparticle voids (Figure 2A). Consistent with these observations, the two-dimensional apparent pore size distribution derived from the SEM images shifted towards larger sizes, with the mean apparent pore size increasing from 0.33 to 0.59 μ m (Figure 2B) [17]. Previous studies found that thermal treatment enriched the Al-bearing fraction of DWS [27], while porous skeleton builders improved sludge dewatering by maintaining water transport pathways [17,28]. These findings are consistent with the Si-, Al- and Fe-rich composition and enlarged apparent pores observed here.

HDWS produced different dose-dependent responses during filtration and subsequent low-temperature drying (Figure 3). SRF initially decreased with increasing HDWS dosage and then increased, reaching its minimum at 30% DS. This non-monotonic response suggests that an appropriate HDWS dosage helped preserve filtration pathways within the cake, whereas further addition increased the solids loading and may have promoted the deposition of fine particles within existing flow channels. The result is consistent with the commonly reported existence of an optimum dosage range for particulate skeleton builders [16]. In contrast with SRF, the residual water content after 30 min of drying at 60 °C decreased continuously with the HDWS dosage and reached a minimum of 35.66% at 60% DS. Thus, the dosage producing the lowest filtration resistance did not coincide with that producing the lowest water content after drying. This divergence indicates that the dosage optimum depends on the evaluated process endpoint and cannot be determined from SRF alone. HDWS conditioning improved both filtration and low-temperature drying, but the optimum dosage depended on the targeted unit operation: 30%

DS was most favorable for filtration, whereas 60% DS produced the best drying performance under the conditions tested.

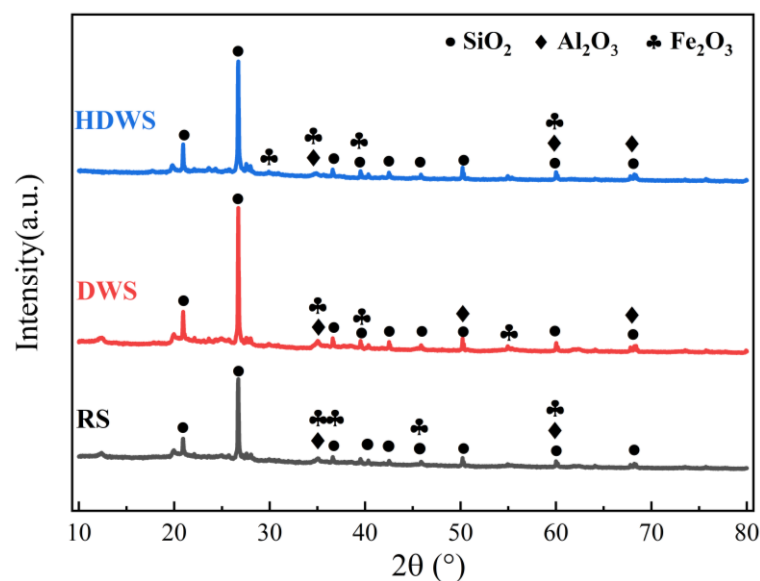


Figure 1. X-ray diffraction patterns of RS, DWS and HDWS.

Table 2. Relative oxide compositions of RS, DWS and HDWS determined by XRF (wt.%).

Samples	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	P ₂ O ₅	CaO	K ₂ O	MgO	MnO	TiO ₂	Others
RS	16.31	15.71	3.36	5.63	1.35	1.22	0.90	0.16	0.28	55.08
DWS	48.26	22.41	4.93	0.54	0.37	2.16	0.54	0.18	0.51	20.10
HDWS	58.68	25.90	6.49	0.68	0.47	2.71	0.58	0.22	0.66	3.61

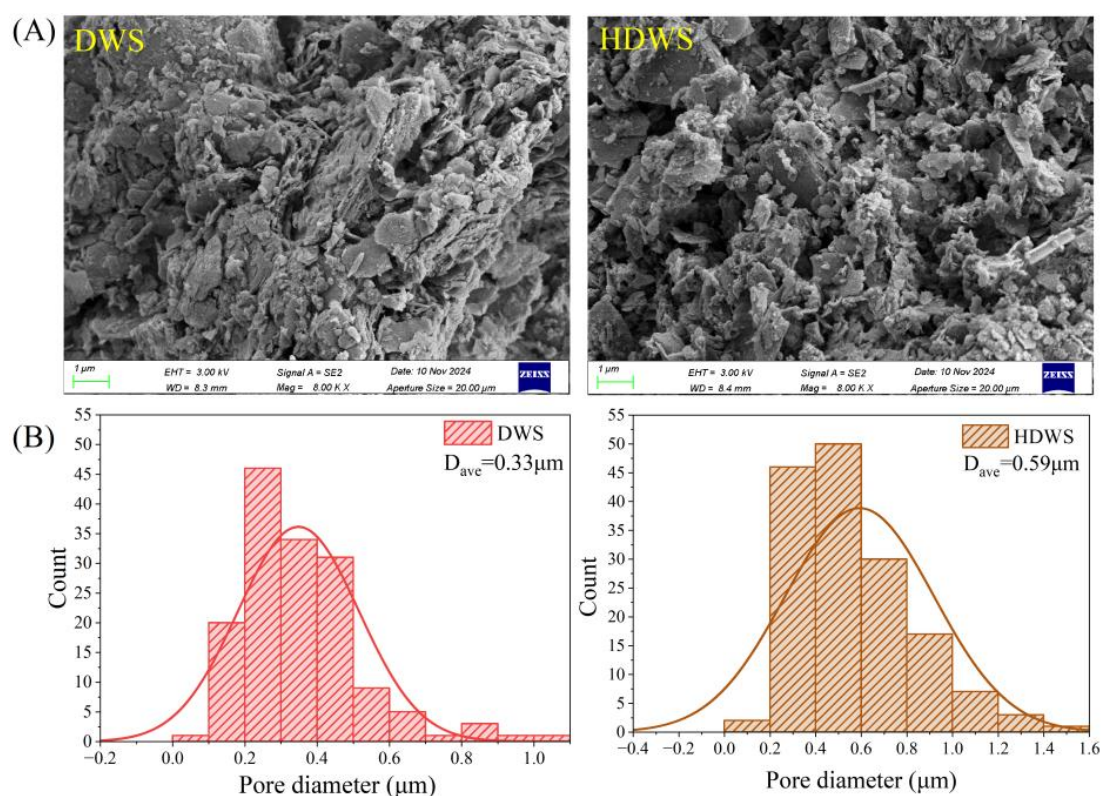


Figure 2. Surface morphologies and two-dimensional apparent pore size distributions of DWS and HDWS: (A) SEM images and (B) apparent pore size distributions.

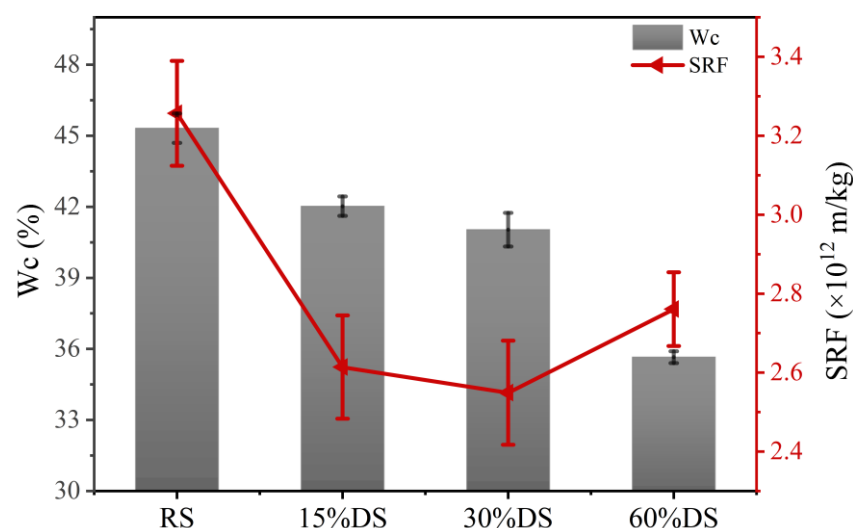


Figure 3. Effects of HDWS dosage on sludge-specific resistance to filtration and water content after 30 min of low-temperature drying at 60 °C.

3.2. Rheological and Textural Responses of Sludge in the Viscoplastic Regime to HDWS Conditioning

The Jenike shear stress decreased moderately but consistently with an increasing HDWS dosage, from approximately 565 Pa for RS to approximately 490 Pa at 60% DS (Figure 4). This parameter represents the resistance of paste-like sludge to bulk shear failure rather than the viscosity of its liquid phase [22]. Its reduction, therefore, indicates that HDWS weakened the overall shear-bearing capacity associated with interparticle bonding and the continuity of the sludge colloidal network. Wang et al. used rheological measurements to relate the structural stability and yielding behavior of acid-conditioned sludge to its dewatering performance [21], whereas Peeters et al. showed that inorganic conditioning could mitigate the operational difficulties associated with the sludge sticky phase during dewatering and drying [23]. In contrast with these chemical-conditioning approaches, HDWS reduced the macroscopic shear resistance through the incorporation of dry mineral particles without strong acidification or high dosages of soluble coagulants. The resulting reduction in bulk shear resistance could potentially facilitate the handling, fragmentation, and spreading of mechanically dewatered cakes before low-temperature drying [8].

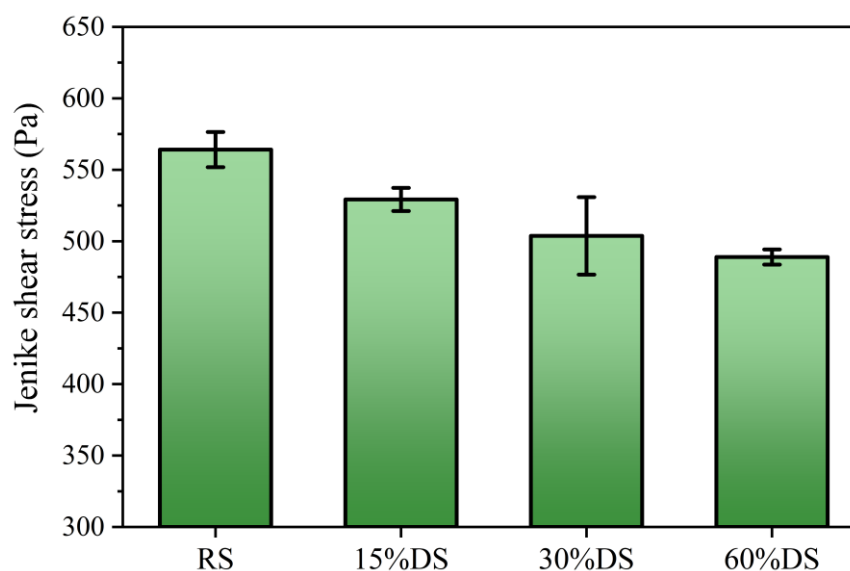


Figure 4. Effect of HDWS dosage on the Jenike shear stress of sludge.

Oscillatory strain amplitude sweeps revealed a dose-dependent restructuring of the sludge network (Figure 5A). Within the linear viscoelastic region, the complex modulus, G^* , of the 15% DS treatment was slightly lower than that of RS, whereas G^* increased markedly at HDWS dosages of 30 and 60% DS. This response suggests that a low HDWS dosage primarily disrupted the original colloidal network, while increasing particle–particle contacts and load-bearing interactions became more important at higher dosages. All treatments entered the modulus decay region at a strain amplitude of approximately 1.15%, indicating that HDWS altered the initial small-strain stiffness without substantially shifting the onset of nonlinear deformation. The LAOS results provided further insight into the deformation-scale dependence of the conditioned sludge (Figure 5B). The large-strain modulus, G'_L , increased at HDWS dosages of 15 and 30% DS. At 60% DS, however, both G'_L and G'_M , together with the LAOS-derived dynamic viscosity parameters, η'_M , decreased substantially. In particular, the minimum-rate dynamic viscosity decreased progressively with an increasing HDWS dosage. These parameters describe the redistribution of elastic energy storage and viscous dissipation within an individual oscillatory cycle [32,35]. The response at 60% DS should, therefore, not be interpreted as uniform structural softening. Instead, the increased G^* in the small-strain region coexisted with lower elastic and viscous resistance under large nonlinear deformation. This combination is consistent with a particle-supported structure that remains relatively stiff under small perturbations but offers less resistance once driven beyond the linear regime. Studies by Liang et al. and Mouzaoui et al. have likewise shown that the mechanical response of concentrated, paste-like sludge depends strongly on the imposed deformation mode and strain scale and cannot be adequately described by a single modulus or viscosity [7,8].

The apparent yield stress and texture analysis results were broadly consistent with the oscillatory rheology (Figure 6A). The apparent yield stress decreased from approximately 670 Pa for RS to approximately 380 Pa at 60% DS. All HDWS-conditioned cakes exhibited lower hardness than RS, although the hardness increased slightly as the HDWS dosage increased from 15 to 60% DS. This response suggests that higher HDWS dosages partially restored particle-mediated load-bearing capacity but did not re-establish the large-deformation compressive strength of the original colloidal sludge network. Adhesiveness decreased sharply after HDWS addition, while cohesiveness declined progressively with increasing dosage (Figure 6B). These changes indicate a reduction in both cake-surface adhesion and the ability of the internal cake structure to withstand repeated compression. The decrease in adhesiveness is consistent with the mitigation of sludge stickiness by inorganic conditioning reported by Peeters et al., although the mechanism here differs because HDWS acts primarily as a particulate mineral amendment [23]. Taken together, the lower Jenike shear stress, yield stress, adhesiveness, and cohesiveness, combined with the retention of small-strain stiffness at high HDWS dosage, indicate a transition from a strongly interconnected colloidal matrix towards a more weakly bonded, particle-supported structure. Such a structure may be more readily handled and fragmented and may promote surface renewal during subsequent low-temperature drying.

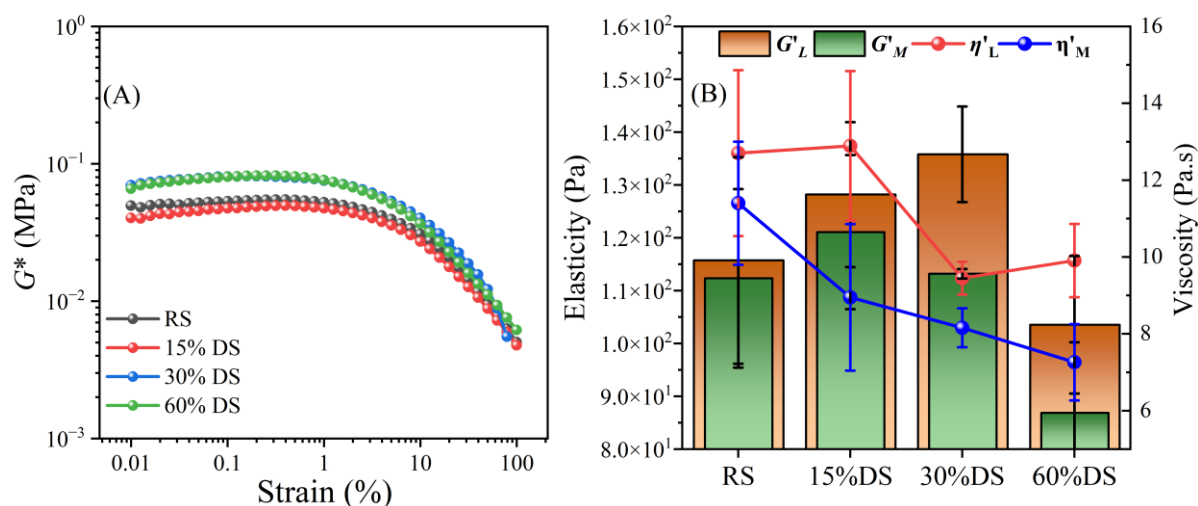


Figure 5. Effects of HDWS dosage on the nonlinear oscillatory rheology of sludge: (A) strain amplitude dependence of the complex modulus G^* ; (B) G'_L , G'_M , η'_L , and η'_M .

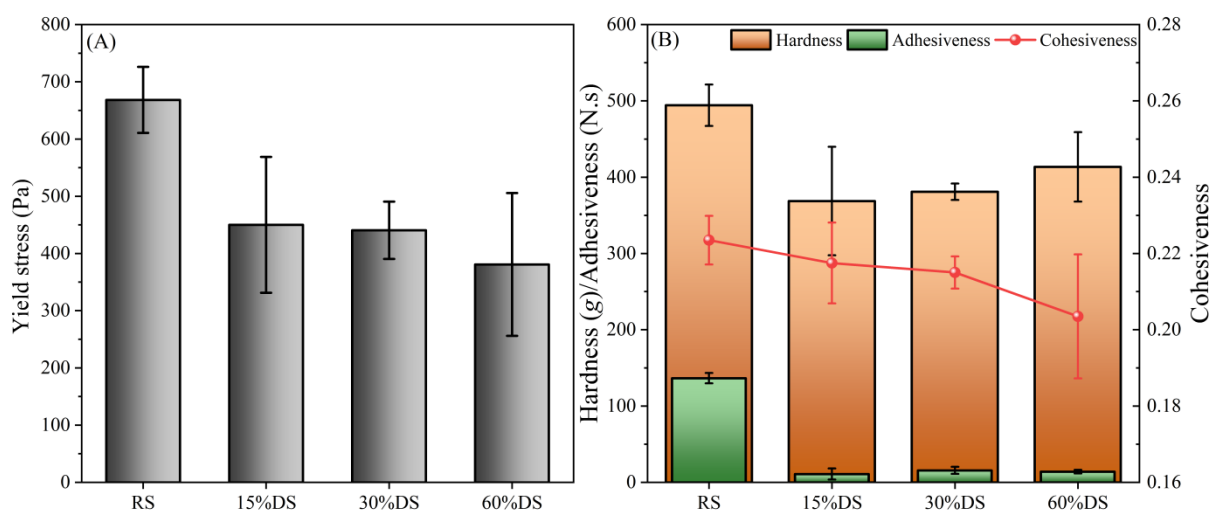


Figure 6. Effects of HDWS dosage on the rheological and texture profile characteristics of sludge: (A) yield stress; (B) hardness, adhesiveness, and cohesiveness.

3.3. Effects of HDWS Conditioning on Low-Temperature Drying and Energy-Related Properties

At 60 °C, the water content of all sludge cakes decreased continuously with drying time, while HDWS addition markedly accelerated water removal (Figure 7A). The 60% DS treatment maintained the lowest water content throughout the drying process, requiring approximately two-thirds of the time needed for RS to reach a water content of 20%. In terms of the absolute drying rate, all treatments exhibited rapid moisture loss at high water contents, followed by a pronounced decrease once the water content fell below approximately 60% (Figure 7B). This trend suggests a progressive shift in the rate-controlling mechanism from surface evaporation and capillary water transport to internal moisture diffusion. Previous studies of water distribution in sludge have similarly shown that moisture transport resistance increases as the water content decreases, and that sludge drying generally enters a falling-rate period dominated by internal diffusion [36,37]. Peeters et al. further reported that sludge undergoes a pronounced sticky phase during the transition from mechanical dewatering to thermal drying, during which particle adhesion and structural shrinkage can substantially restrict heat and mass transfer; inorganic conditioning can mitigate these adverse effects [22]. Taken together with the reductions in adhesiveness, cohesiveness, and yield stress described above, the enhanced drying performance of

HDWS-conditioned cakes was more likely associated with weakened cake bonding and shrinkage and shorter internal moisture transport pathways, rather than solely with the apparent decrease in water content caused by the addition of dry solids.

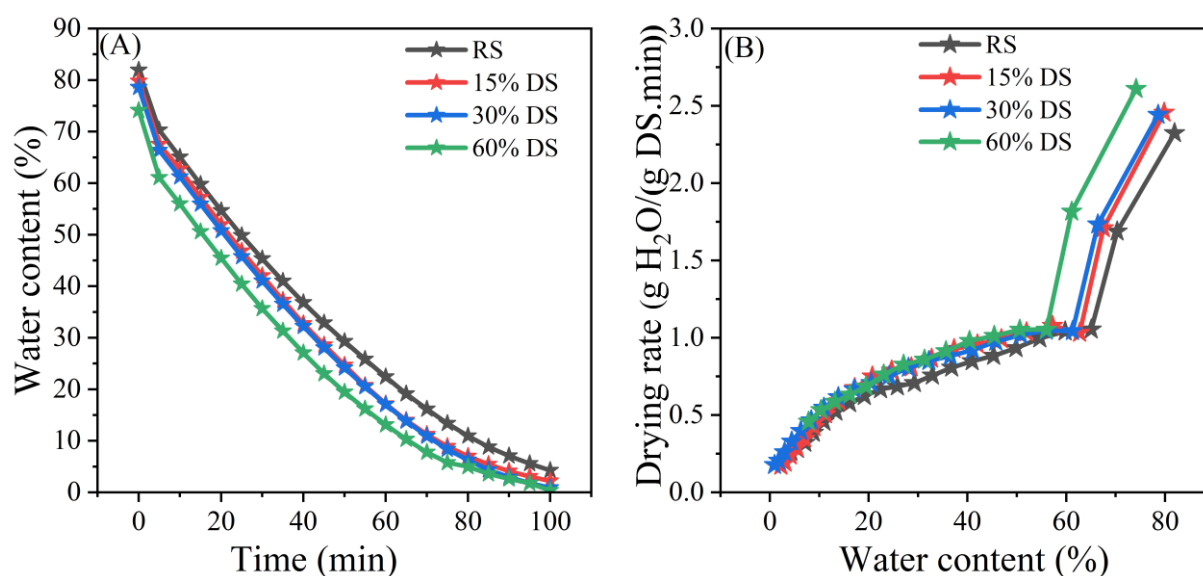


Figure 7. Effects of HDWS dosage on sludge drying at 60 °C: (A) water content evolution; (B) positive water loss rate as a function of water content.

HDWS addition also altered the drying energy consumption and fuel properties of the sludge cake (Figure 8). At a target water content of 20%, the cumulative electricity consumption decreased from approximately 1.86 kWh for RS to approximately 1.34 kWh for the 60% DS treatment, representing a reduction of approximately 28%, consistent with the shorter drying time. Deng et al. also emphasized that regulating cake structure and water status through upstream treatment is an important means of reducing the energy demand of subsequent thermal drying in coupled mechanical-dewatering–thermal-drying processes [14]. However, because HDWS contained a high proportion of non-combustible inorganic components, its addition decreased the calorific value of the sludge cake from approximately 9.6 kJ g^{−1} for RS to approximately 4.3 kJ g^{−1} for the 60% DS treatment, a reduction of more than 50%. The reduction in drying energy consumption was, therefore, accompanied by a loss of fuel energy density. If the dried cake is subsequently used for incineration or fuel recovery, a high HDWS dosage may not provide the best overall energy performance. In contrast, the increased ash content may be less consequential when the cake is intended for construction material production or other mineral resource recovery routes. The optimum HDWS dosage should, therefore, not be determined solely from drying electricity consumption, but should be evaluated by considering the specific energy consumption per unit mass of water removed, the reduction in calorific value, and the intended downstream management route.

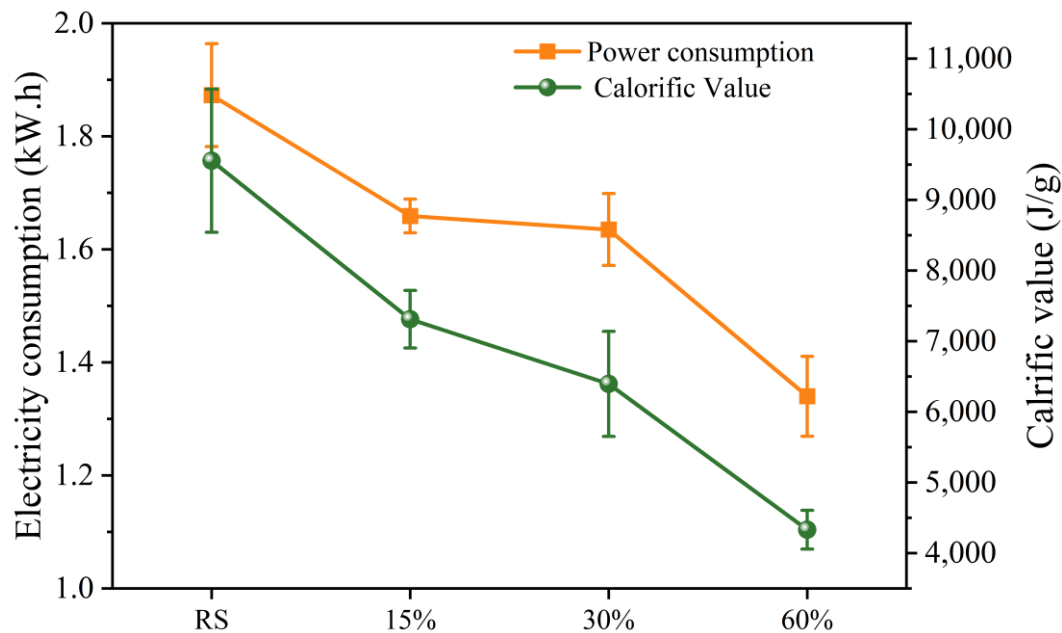


Figure 8. Effects of HDWS dosage on the electricity consumption during low-temperature drying and the calorific value of sludge.

3.4. Interpretation and Process Implications of HDWS Conditioning

Taken together, the preceding results indicate that HDWS did not simply “dilute” or “soften” the sludge, but restructured the load-bearing and energy-dissipation behavior of the mechanically dewatered cake. In RS, the continuous organic colloidal network resulted in relatively high shear stress, yield stress, adhesiveness, and cohesiveness. As the HDWS dosage increased, both the Jenike shear stress and apparent yield stress decreased progressively (Figures 4 and 6A), accompanied by reductions in adhesiveness and cohesiveness (Figure 6B). These changes indicate that the macroscopic bonding and large-deformation resistance of the original sludge network were weakened. Meanwhile, the 30 and 60% DS treatments retained relatively high complex moduli within the linear viscoelastic region, whereas the nonlinear elastic and viscous parameters decreased at high HDWS dosages (Figure 5). HDWS, therefore, did not simply soften the system; rather, it likely shifted part of the load-bearing function from the continuous organic network to contacts among dispersed inorganic particles. Peeters et al. similarly observed reduced adhesion and operational resistance when PACI was used to regulate the sludge sticky phase [23], while Wang et al. showed that conditioning-induced changes in yielding and rheological behavior can reflect the restructuring of sludge network stability [21]. Studies of skeleton-building materials have also demonstrated that rigid particles can mitigate cake compaction and improve conditions for moisture transport [16,18]. Unlike chemical coagulation or the addition of conventional external skeleton builders, HDWS addition may have promoted physical restructuring through matrix partitioning and localized particle support; however, this interpretation requires direct microstructural confirmation.

This structural interpretation also explains the different dose responses observed during filtration and drying. The lowest SRF was obtained at 30% DS, whereas the 60% DS treatment produced the lowest water content after drying at 60 °C for 30 min (Figure 3). Consistently, HDWS addition shortened the time required to reach the target water content (Figure 7) and reduced the electricity consumption during drying (Figure 8). Because the energy inputs for HDWS air drying, grinding, thermal treatment and transportation were not quantified, this comparison applies only to the laboratory drying stage

and does not constitute a complete process energy balance or net sustainability assessment. These results show that the minimum filtration resistance does not necessarily correspond to the highest subsequent drying efficiency. Previous studies of HDWS have focused primarily on its capacity to enhance the filtration dewatering of waste-activated sludge [28], whereas the present results indicate that conditioning-induced structural changes may persist into the low-temperature drying stage after mechanical dewatering. However, a high HDWS dosage also increased the proportion of inorganic solids and reduced the calorific value of the cake (Figure 8). The dosage requirement also differs from that of conventional chemical conditioners. Peeters et al. [23] used 50–150 g PACl kg⁻¹ MLSS to mitigate sludge stickiness, while Zhu et al. [38] used 0.15 g FeCl₃ g⁻¹ DS and 0.70 g biochar g⁻¹ DS for combined sludge conditioning. Additional Fe/Al may alter ash fusion behavior and increase sintering or slagging risks during incineration [9]. As HDWS reuses a residual mineral stream, its 60% DS dosage is technically reasonable for waste-derived skeleton building; however, the dosage should be selected according to preprocessing requirements and the intended downstream route. At a dosage of 60% DS, 0.60 kg of HDWS was added per kilogram of original sludge dry solids, thereby increasing the final dry-solids mass and potential ash generation. Moreover, the local availability of DWS and the requirements for air drying, grinding, thermal treatment, and transportation should be considered when assessing engineering feasibility. The 60% DS treatment, therefore, represents the best-performing laboratory drying condition under the conditions tested rather than an overall engineering optimum. Its engineering dosage should, therefore, be selected according to the intended downstream route. This assessment should also consider trace metal risks. Because trace metals were not quantified in the present DWS or HDWS and their occurrence varies with source water and treatment chemicals, site-specific total-metal and leaching analyses are required before land application or resource recovery. For low-temperature drying followed by construction material production, greater emphasis may be placed on cake structure and drying energy consumption [6,15]. For incineration or fuel recovery, both the specific energy consumption for water removal and the loss of calorific value must be considered. The selection and development of sludge-conditioning strategies should therefore be guided by whole-process volume reduction efficiency rather than by a single filtration indicator. More broadly, whole-process sludge management should evaluate upstream sludge minimization together with the dewaterability and downstream handling of the residual sludge. Recent intermittent aeration IFAS-OSA systems achieved very low net sludge production while maintaining acceptable or good dewaterability, illustrating the value of integrating source reduction with downstream sludge management [39,40].

4. Conclusions

This study evaluated HDWS as a sludge-derived mineral conditioner for coupling mechanical dewatering with subsequent low-temperature drying. The main conclusions are as follows:

- HDWS exhibited a Si-, Al-, and Fe-rich oxide composition and a rougher particle morphology with more open interparticle voids than DWS, supporting its evaluation as a mineral-rich conditioner.
- HDWS exhibited process-specific dose responses across the dewatering–drying sequence. The lowest SRF was obtained at 30% DS, whereas the 60% DS treatment achieved the lowest water content of 35.66% after low-temperature drying and only required approximately two-thirds of the RS drying time to reach 20% water content.
- The progressive reductions in Jenike shear stress, apparent yield stress, adhesiveness, and cohesiveness, together with the retention of small-strain stiffness at higher HDWS dosages, were consistent with, but do not directly demonstrate, a possible

redistribution of load bearing towards less strongly bonded inorganic particle contacts.

Although the 60% DS treatment reduced the recorded drying electricity consumption by approximately 28%, it also decreased the cake calorific value by more than 50%. Therefore, it should not be interpreted as an overall engineering optimum. The optimum HDWS dosage should, therefore, be determined across the entire dewatering–drying sequence and according to the intended downstream management route.

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