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Effect of calcium sulfate dehydrate and external electric field on the sedimentation of fine insoluble particles

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ABSTRACT

Several reports show that calcium sulfate dehydrate can induce the sedimentation of insoluble substances in waste water. Silt, clay, and feldspar were selected in this study to settle with calcium sulfate dehydrate in water, and the parameters of particle interaction were calculated using the extended DLVO theory. Results indicate that the key to sedimentation is the electrostatic force between particles. Electrostatic force facilitates cosedimentation of calcium sulfate dehydrate with silt or clay, but not with feldspar, and their combination is weak. External electrical field can promote the sedimentation of silt, clay, and humic acid but not the cosedimentation of calcium sulfate dehydrate with insoluble substances. Moreover, an external electric field can facilitate the dispersion of clay and calcium sulfate dehydrate aggregates. Most of the electron charges after the cosedimentation of calcium sulfate dehydrate and silt was neutralized, but a certain amount of electron charge remained after the combination of clay and calcium sulfate dehydrate. Suspended particles in water continued to increase after the sedimentation of feldspar and calcium sulfate dehydrate, thereby implying that new nuclei must have been discharged by calcium sulfate dehydrate.

Keywords: Coagulation; Gypsum; Extended DLVO theory; Insoluble particle

1. Introduction

Calcium sulfate dehydrate in water is avoided in all water treatment techniques because it easily attaches to the walls of devices made of various materials, resulting in scaling. Calcium sulfate dehydrate is slightly soluble, difficult to remove, and capable of multiplying at its original growth site. Calcium sulfate dehydrate is mostly considered as industrial waste. Nevertheless, it has also been studied because of its easy attachment to other materials, thus suggesting its application as coagulant. Experimental results have been satisfactory, but its use as coagulant remains a controversy.

The applications of calcium sulfate dehydrate as coagulant is largely described in the literature with regard to fine silt sedimentation in water. Fine silt is stable in water as colloid, and it does not easily settle using conventional thickeners or flocculants. Phosphogypsum, which is used as a cheap water-clarifying agent, was employed as the pre-product of muddy water clarification [1]. This agent was found to destabilize colloidal suspensions and allows the removal of fine clay species in water, thus increasing water quality and reusability. In primary waste water treatment, calcium sulfate dehydrate has the same effect as

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traditional aluminum sulfate flocculant [2]. The resultant pH of water is lower than four after addition of aluminum sulfate, but pH 7 is needed when aluminum sulfate is used as flocculant. Thus, additional agentia is required. Apart from calcium sulfate dehydrate, lime can also promote the sedimentation of clay minerals. However, the use of lime causes an increase in pH from 7 to 10.5. The great advantage of calcium sulfate dehydrate is the relatively stable pH that is maintained in solution, i.e. large pH changes do not occur. In spite of the good sedimentation accelerating effect, toxicity tests reveal that calcium sulfate dehydrates induce algal growth in water [1].

Coagulation between particles is usually related to its surface properties, including surface charge. Most clay minerals can exchange ions. Thus, the sedimentation of clay and calcium sulfate dehydrate suggests that calcium sulfate dehydrate dissolves and discharges Ca^{2+}, which replaces the surface particle Na^+ or other monovalent ion. This effect could result in an unstable liquid colloid. Quartz suspension was employed to conduct condensation experiments for verifying the calcium dehydration/destabilization mechanism of Ca^{2+} in accelerating the sedimentation of insoluble particles [3]. Ca^{2+} is an inorganic flocculant that can compact a diffused double layer on the surface of clay particles. This effect results in a thinner hydrated shell, reduces ζ electric potential, causes clay chip surface-to-surface and end-to-surface coalescence, and decreases particle dispersion degree. The mechanism of charge neutralization and compression of the double layer is usually used to explain the enhancement of sedimentation and dewater tailings. Other calcium compounds can similarly separate insoluble substances in water. For instance, calcium lactate was used as coagulant–flocculant to remove suspended solids in water [4], and water turbidity is significantly reduced in 2 h, thus decreasing from 300 to 2.5–5.5 NTU after 18 h. The slight acidity also induces the decrease in turbidity. The influence of ionic strength on suspension stability was also studied using spectroscopy [5]. The clay particles have approximation–association processes with time, which can change the spectrum in the suspensions. It was proved that the increase of ionic strength can assist the particle–particle approximation–association processes. Cosedimentation sometimes occurs in chemical reactions. Brownian aggregation is a process either diffusion or reaction limited. For instance, in water containing boric acid, calcium sulfate dehydrate can precipitate almost all boracic acid [6], which may be caused by the reaction between boracic acid and calcium sulfate dehydrate and the formation of ettringite.

Microscopic action between particles is a manifestation of their surface properties. One of the causes of cosedimentation is the micro-attraction force between particles, which can be measured by atomic force microscopy [7] and described by the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory. DLVO theory is usually used to predict the interaction between particles in a liquid medium. Further, the electrical double layer repulsions calculated using the classical DLVO theory represented one-half of the interactions occurring in aqueous systems. When water was used as the liquid medium, most of the forces need to be calculated using the extended DLVO theory because the polar interaction energies always occurs [8]. Moreover, appropriate Ca^{2+} and Mg^{2+} addition in water could strengthen the attraction force between particles, which can explain the ability of calcium sulfate dehydrate to flocculate and settle insoluble substances in oil sand treatment. Electrostatic force is the key to particle coagulation or dispersion. Many suspended particles are charged, and external electric field affects their sedimentation. Thus, the interference of external electric field can be used to study sedimentation [9]. Upon application of an electric field of 150 V/m into water containing 14.4% of silt [10], the settlement velocity of silt doubles, and the height of the ultimate hierarchical interface of silt and water is reduced by half. The application of external electric field has a better performance in accelerating sedimentation compared to ferric chloride as flocculant. In the treatment of water loaded with solid particles, flocculant addition under an external electric field reduces the height of hierarchical interface of silt and water by half compared with using flocculant alone. In a study on coagulation with an external electric field during the sedimentation of charged aerosol particles [11] wherein the change in Coulomb force was calculated, external electric field was found to accelerate particle coagulation. The external electric field accelerates the coagulation for both symmetric bipolar charged particles and asymmetric charged ones, while the electrostatic dispersion only accelerates the coagulation for asymmetric charged particles. Electric double layer or microscopic force can be investigated by dynamic light scattering. For instance, faster coagulation is found in laponite particles when the electrolyte concentration in the suspension increases because net particle charge changes, which weakens the electrostatic repulsion between particles [12]. Increased pH value reduces the positive charge of particles and slows down coagulation. Meanwhile, microscopic force can be changed with the dialysis method [13]. For example, after a montmorillonite suspension underwent dialysis, its surface area was increased and the coagulation state was modified. The decrease in cations caused an exponential increase in the repulsion between particles, thus segregating the soil particles into layers due to osmotic swelling.

The effects of sedimentation acceleration vary according to the insoluble substance because of the different surface properties and the microscopic force. Clay, silt, and other silicates have different characteristics. Thus, their cosedimentation with calcium sulfate dehydrate also varies. Epi-fluorescence microscopy [14] is employed in studies on the coagulation of crude oil and clay particles to observe the size of aggregates; if it increases with the increase in salinity, such an increase is linked with the clay type. Molecular simulation indicates that an absorption mechanism exists in particle aggregates, or a bridging connection links the particles, leading to particle cosedimentation [15]. The adsorption energies depend on the interacting area, which is obviously related to the clay type. Particle aggregation of insoluble sedimentation is important for understanding the migration and transformation of pollutants discharged into natural water [12], such as oil drilling fluids, thickeners in cosmetics and pharmaceuticals, and additives to building materials. The current paper aimed to investigate the cosedimentation effects of different insoluble substances and calcium sulfate dehydrate and to discuss the role of microscopic force in cosedimentation.

2. Theoretical and experimental details

2.1. Configuration of sedimentation experiment

We conducted the sedimentation experiment using a Bunsen beaker containing 1,000 mL of deionized water. A mixture of 10 g of ground and sieved 200 mesh calcium sulfate dehydrate (or anhydrous calcium sulfate, hemihydrate calcium sulfate) and 10 g of insoluble substance (or total 20 g of insoluble substance without calcium sulfate dehydrate) was placed into the beaker, stirred and mixed for 2 min. Then the samples were left for sedimentation. Insoluble substances were also added into the calcium sulfate saturated liquid to observe their sedimentation. Samples were obtained from the center of the beaker using a sampler. Turbidity was detected with a turbidimeter (HACH 2100AN, USA), and particle size distribution was measured by a particle monitor (Mettler FBRM G400, Switzerland) assisted particle size analyzer (ANKERSMID EyeTech, Netherlands). The insoluble substances included clay (kaolinite and montmorillonite), silt (quartz), feldspar (potassium feldspar and albite), and humic acid. After sampling, sedimentation was analyzed with X-ray diffraction (XRD, Diffractometer D8, Bruker, Germany), Fourier transform infrared spectroscopy (Perkin Elemer Frontier Pyris.1, USA), and scanning electron microscopy (SEM, JEOL JSM-6701F, Japan). To detect the charge features after particle coagulation, an external electric field was applied. Electrodes were placed on the surface and at the bottom of the suspension, and 120 V/m of direct current was applied. When the positive electrode was on the above the electric field was marked with "+", and conversely, the electric field was marked with "−".

2.2. Measurement and calculation of the extended DLVO potential energy

Extended DLVO theory [16–18] is used to explain the stability of colloidal suspension. According to the extended DLVO theory, the total potential energy, V_T, determines the coagulation or dispersion between particles. Given that $V_T > 0$, particle repulsion and dispersion occur. Under contrasting conditions, particle attraction and coagulation occur. The calculation is as follows [19]:

$$V_T = V_E + V_W + V_H \tag{1}$$

where V_E is the electrostatic energy between particles, V_W is the Van der Waals interaction energy between particles, and V_H is the polarization energy between particles. The forces related to V_W and V_E are the Van der Waals attraction and electrostatic repulsion forces, respectively.

For the spherical particles with radii R_1 and R_2,

$$V_W = -\frac{A_{132}}{6H} \cdot \frac{R_1 R_2}{(R_1 + R_2)} \tag{2}$$

where H is the particle spacing and A_{132} is the effective Hamaker constant of substance 1 and 2 which interact in medium 3. Additionally, A_{132} can be calculated as follows:

$$A_{132} \approx \left(\sqrt{A_{11}} - \sqrt{A_{33}}\right)\left(\sqrt{A_{22}} - \sqrt{A_{33}}\right) \tag{3}$$

where A_{11}, A_{22}, and A_{33} are the Hamaker constants of substances 1, 2, and 3, respectively, which are interacting in a vacuum.

The electrostatic interaction energy, V_E, between particles is as follows:

$$V_E = \frac{\pi \varepsilon_a R_1 R_2}{R_1 + R_2} \left(\psi_{01}^2 + \psi_{02}^2\right) \left[\frac{2\psi_{01}^2 \psi_{02}^2}{\psi_{01}^2 + \psi_{02}^2}\ p + q\right] \quad (4)$$

where $p = \ln\left[\frac{1+\exp(-\kappa H)}{1-\exp(-\kappa H)}\right]$ and $q = \ln\left[1-\exp(-2\kappa H)\right]$. ψ_{01} and ψ_{02} are the surface potentials of particle 1 and 2, respectively, and can be replaced by ζ potential. ε_a is the absolute dielectric constant of the dispersed medium. κ^{-1} is the reciprocal of the Debye length, which represents the thickness of the electric double layer.

$$\kappa = \left(\frac{8\pi e^2 C Z^2}{\varepsilon_a K T}\right)^{1/2} \quad (5)$$

where C is the ionic concentration of the substance concentration, e is the electron charge (1.602×10^{-19} C), Z is the valence of the ion, T is the absolute temperature, and K is the Boltzmann constant (1.38×10^{-23} J/K).

The correlation between the interface polar interaction energy and distance is:

$$V_H = \frac{2\pi R_1 R_2}{R_1 + R_2}\ h_0 V_H^0 \exp\left(\frac{H_0 - H}{h_0}\right) \quad (6)$$

where H_0 is the surface distance of the two particles, h_0 is the decay length, and ${V_H}^0$ is the energy constant of the interface polar interactions. In addition, ${V_H}^0$ is determined by the following expression:

$$V_H^0 = 2\left[\sqrt{r_3^+}\left(\sqrt{r_1^-} + \sqrt{r_2^-} - \sqrt{r_3^-}\right) + \sqrt{r_3^-}\left(\sqrt{r_1^+} + \sqrt{r_2^+} - \sqrt{r_3^+}\right) - \sqrt{r_1^+ r_2^-} - \sqrt{r_1^- r_2^+}\right] \quad (7)$$

where r^{1+}, r^{2+}, and r^{3+} are the electron acceptor components of the surface energy of particles 1, 2, and medium 3, respectively. In addition, r^{1-}, r^{2-}, and r^{3-} are the electron donor components of the surface energy. r^{1+}, r^{1-}, r^{2+}, and r^{2-} can be calculated by the following equation:

$$(1 + \cos\theta) r_L = 2\left(\sqrt{r_s^d r_L^d} + \sqrt{r_s^+ r_L^-} + \sqrt{r_s^- r_L^+}\right) \quad (8)$$

where r_L and ${r_L}^d$ are the liquid surface energy and the surface energy dispersion parameters, respectively. r_L^+ and r_L^- are the electron acceptor and donor components, respectively. r_s^d, r_s^+, and r_s^- represent the dispersion components of solid surface energy, electron acceptor component, and electron donor component. θ is the surface contact angle between the liquid and the solid.

In the mud-water system, an empirical relation exists between the solid surface Hamaker constant (A_S) and the contact liquid surface Hamaker constant (A_L) as follows [19]:

$$A_L = 4A_S/(1 + \cos\theta)^2 \quad (9)$$

In calculation, the water Hamaker constant is 4.84×10^{-20} J and the water absolute dielectric constant is 7.172×10^{-10} F/m. To determine V_T, a Zeta Potential Analyzer (Nano ZS90, England) was used to detect ζ potential of the suspension. The ζ potential of the calcium sulfate dihydrate changes over time. In that case, the data of ζ potential were read at the fourth minute after the calcium sulfate dihydrate was put into the water, when the sedimentation began. In addition, a contact angle meter (JC2000C1, China) was used to measure the contact angle. Different contact angles of various crystal surfaces were not considered, but the means of the measured contact angles were calculated.

3. Results and discussion

3.1. *Influence of Ca^{2+} and calcium sulfate dehydrate on the sedimentation of insoluble substances*

Fig. 1 shows the turbidity changes along with time in the saturated solution of calcium sulfate with slime

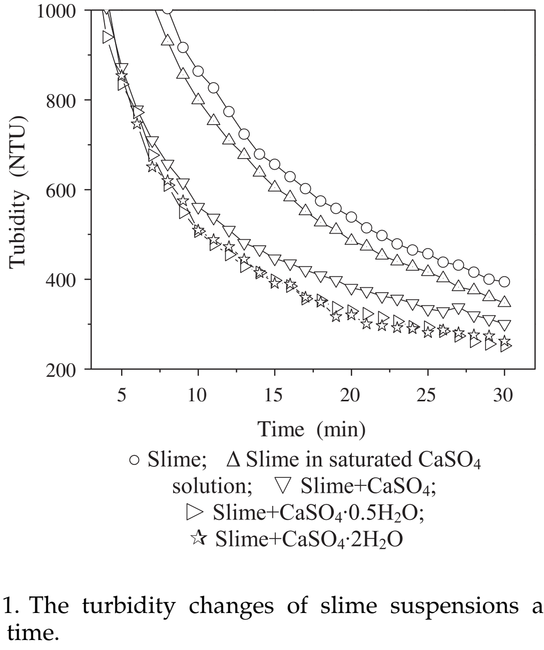


Fig. 1. The turbidity changes of slime suspensions along with time.

(including 40–45% feldspar, 15–20% silt, 20–30% clay, and 5–10% calcium sulfate dehydrate) and in the suspension of slime added into calcium sulfate with different crystal water. The sedimentation of slime in the saturated solution of calcium sulfate was accelerated, which indicates that Ca^{2+} was effective in the slime sedimentation. One of the reasons may be ion exchange. Ca^{2+} can replace Na^+ on the particle surface in the form of hydrated $Ca(OH)^+$ solution species or hydrolyzable calcium species, which resulted in the elimination of the hydration forces and the contact between particles [3]. Moreover, most of the surfaces of insoluble substances are negatively charged. Ca^{2+} is absorbed on the insoluble substance surface and releases a hydrogen ion. An external negative charge on the surface of the insoluble substances is observed, whereas a positive charge of Ca^{2+} remains. Therefore, regions of positive and negative charges exist among the insoluble particles, which lead to coagulation [20].

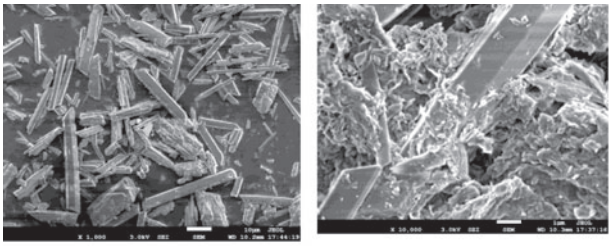
Fig. 1 indicates that calcium sulfate with different crystal water has similar effect on accelerating fine slime sedimentation. In the suspension with solid calcium sulfate, the sedimentation tendency of slime is more significant, which indicates that apart from Ca^{2+} the solid calcium sulfate particles can also promote the sedimentation of slime. Fig. 2 shows the SEM images of calcium sulfate dehydrate and of various minerals with calcium sulfate dihydrate after cosedimentation. The pillar-like crystals in the figure represent calcium sulfate dehydrate, and the regiment-like or bulk substances are other insoluble substances. Results show that clay and silt minerals can conglutinate staggeredly with calcium sulfate dehydrate, whereas feldspar weakly combines with calcium sulfate dehydrate.

Furthermore, Fig. 2 shows that clay and silt mostly conglutinate with the side surface of calcium sulfate dehydrate. Calcium sulfate dehydrate generally belongs to the monoclinic system. Ca^{2+}, together with SO_4^{2-} tetrahedron, forms a double-deck structure, where H_2O molecules are distributed. The crystal side is parallel with its double-deck structure, on which Ca^{2+} and SO_4^{2-} are densely distributed, increasing the atomic density with a high amount of charge. Thus, it is easy to combine with other substances. With silt as an example, Fig. 3 shows the IR spectroscopy results after the cosedimentation of insoluble substances and calcium sulfate dehydrate in water or dry mixed with each other. Both IR spectra have almost the same shapes in the low wave number range (400–1,000 cm^{-1}) where most of the inorganic peaks should be appeared, with no indication of chemical bonds after the cosedimentation of insoluble substances and calcium sulfate dehydrate, thus indirectly confirming that electrostatic force facilitated cosedimentation.

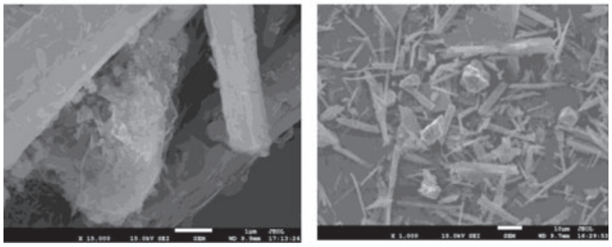
3.2. The extended DLVO interaction between particles

Fig. 4 indicates that when calcium sulfate dehydrate was added into water, the number of particles of different sizes varied with time. More and more particles with sizes smaller than 50 μm were found, demonstrating that new crystals were formed.

Calcium sulfate dehydrate is slightly soluble and releases Ca^{2+} and SO_4^{2-} when dissolved in water or

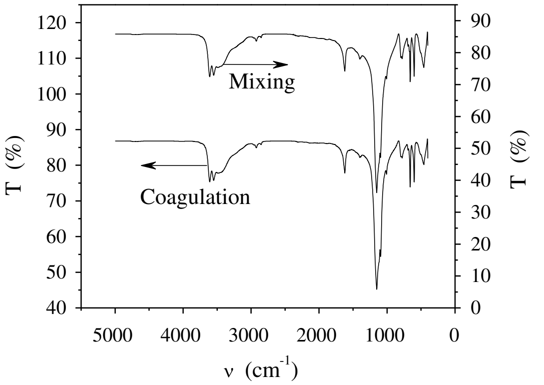


(a) $CaSO_4·2H_2O$ **(b)** Montmorillonite $+CaSO_4·2H_2O$



(c) Quartz $+CaSO_4·2H_2O$ **(d)** Albite$+CaSO_4·2H_2O$

Fig. 2. The SEM images of insoluble substances after cosedimentation.



Insoluble substances: Quartz and $CaSO_4·2H_2O$

Fig. 3. The IR spectra of the cosedimentation and the dry mixture of insoluble substances.

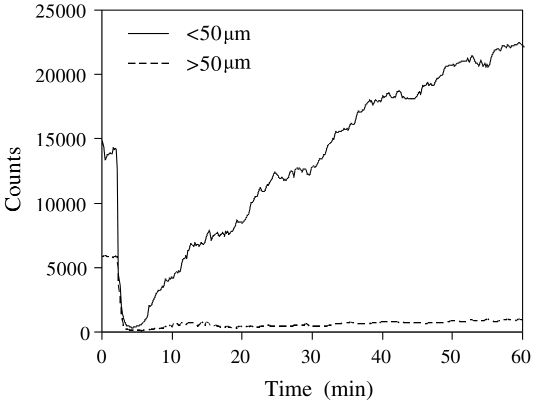


Fig. 4. The number of particles of calcium sulfate dehydrate added into water.

breaks down into new small nuclei. In the presence of solid calcium sulfate dehydrate, saturation and even supersaturation of Ca^{2+} and SO_4^{2-} occur in water. When the concentrations of Ca^{2+} and SO_4^{2-} are too high, calcium sulfate dehydrate easily separates in the form of crystal, and new nuclei are formed, which also grows on the existing calcium sulfate dehydrate crystal surface. In other words, calcium sulfate dehydrate particles multiply and they are difficult to completely eliminate after its addition into water. This effect actually increases the risk of scaling. Samples of the sediments that had settled for 30 min were obtained. Fig. 2(a) shows the SEM image, indicating the various sizes of calcium sulfate dehydrate particles, which were mostly smaller than 50 μm.

Although numerous fine crystals were produced by the addition of calcium sulfate dehydrate to water, cosedimentation was enhanced when calcium sulfate dehydrate and other insoluble substances were simultaneously added to water, which demonstrates that calcium sulfate dehydrate conglutinates with insoluble substances. Montmorillonite and albite were used as examples. Fig. 5(b) and (d) show the time-dependent variation in the number of fine particles in the sedimentation of minerals alone and of the suspension mixture of minerals and calcium sulfate dehydrate. The increasing tendency of small crystals similar to calcium sulfate dehydrate was not found in the mineral particles. In the sedimentation of mineral particles alone, their number decreased or remained stable. As shown in Fig. 5(b) and (d), no new crystal nucleus was formed. Correspondingly, Fig. 5(a)–(c) indicate the electrostatic interactions, Van der Waals interaction energy, and polarization energy varied with particle spacing according to the extended DLVO theory. In

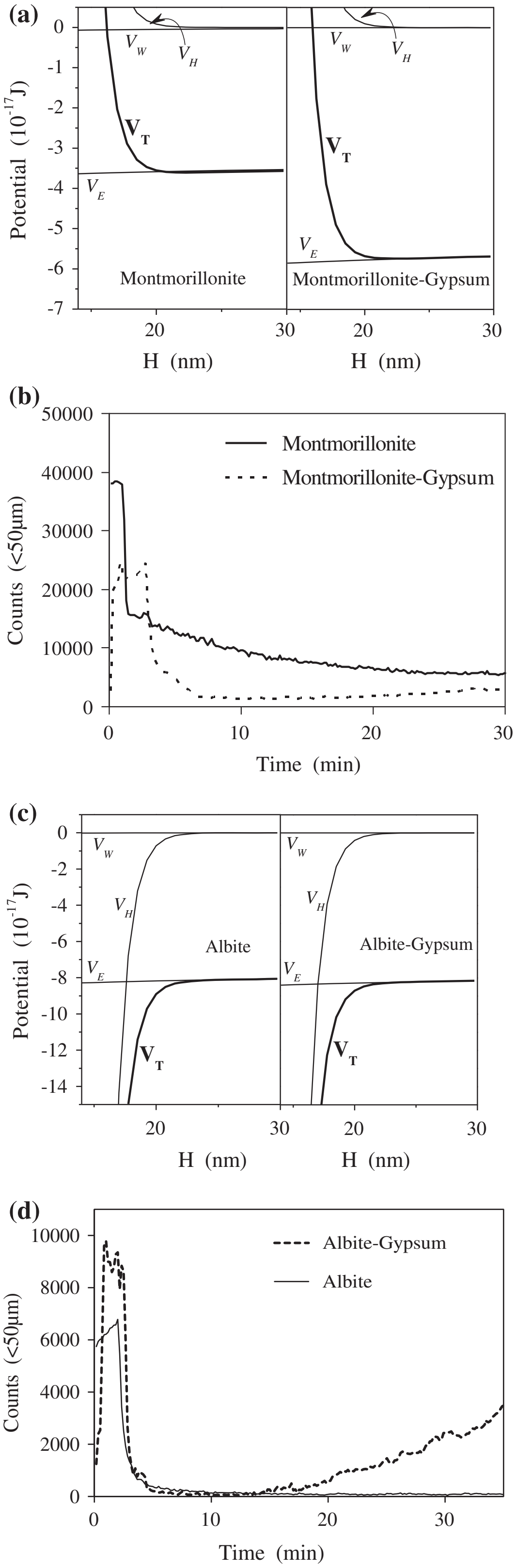


Fig. 5. Extended DLVO interactions and sedimentation of insoluble substances.

Table 1
Parameters required in the calculation of extended DLVO energies

	θ (° water)						
	This work	Literature	ξ (V)	Hamaker (J)	r_s^d (mJ/m^2)	r_s^+ (mJ/m^2)	r_s^- (mJ/m^2)
Montmorillonite	0		−0.0118	9.32×10^{-20} [21]	43.01	0.10	60.60 [19]
Quartz	28	35 [22,23]	−0.0371	4.30×10^{-21} [24]	41.50	0.40	42.40 [23]
Kaolinite	0	0 [19]	−0.0313	8.49×10^{-20} [21]	70.17	0.00	44.70 [19]
Potassium feldspar	52		−0.0324	$3.15 \times 1\ 0^{-20}$	52.67	0.82	34.04
Albite	53		−0.0418	3.11×10^{-20}	29.92	0.53	33.31
$CaSO_4{\cdot}2H_2O$	15	17 [22]	−0.0170	4.63×10^{-20}	47.14	0.00	47.87 [25]

addition, Table 1 shows the required contact angle, Hamaker constant, and surface energy values in the calculation.

The dispersion characteristics of the substances shown in Fig. 5 are categorized into two types. Most minerals, such as silt and clay, exhibit sedimentation similar to that in Fig. 5(a) and (b). Van der Waals interaction between particles is negative, but its absolute value is small. Hence, it contributes minimally to cosedimentation. The polarization between particles indicates hydrophilic repulsion energy, which is not conducive to particle coagulation for sedimentation. However, the electrostatic energy between particles is constantly negative, and the absolute value is large. Thus, the total potential energy becomes negative, and particles more easily agglomerate. Despite the negative V_T of minerals, V_T further decreases after the addition of calcium sulfate dehydrate. Thus, sedimentation is more obvious. Fig. 5 shows that electrostatic force determines the sedimentation of the particles. V_W and V_H change slightly before and after calcium sulfate dehydrate addition to most mineral suspensions. However, V_E is decreased considerably, thereby reducing the total potential energy V_T and catalyzing particle sedimentation. Meanwhile, some samples, such as albite shown in Fig. 5(c), have low V_E and V_T, which also vary little after addition of calcium sulfate dehydrate. No change in sedimentation was found. Due to the self-growth characteristics, fine particles in the liquid phase also increases, as indicated in Fig. 5(d).

Fig. 6 shows V_T after different mineral particles are combined with calcium sulfate dehydrate. Albite is notably exceptional because of its low potential. Based on potential value, the cosedimentation tendency of feldspar minerals and calcium sulfate dehydrate tends to be maximum, followed by clay minerals (kaolin and montmorillonite) and silt minerals (quartz).

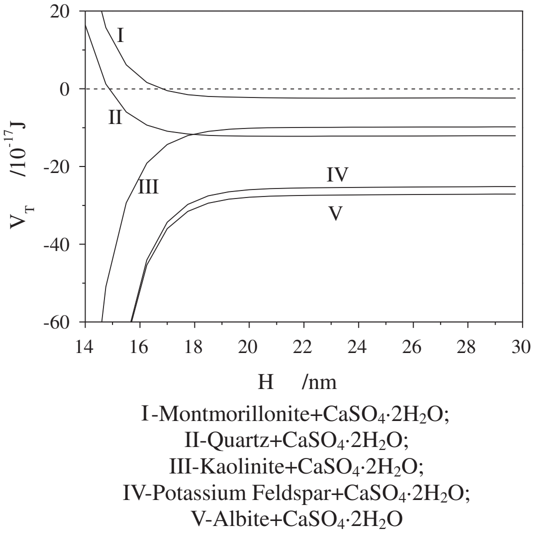


Fig. 6. Potential energies of insoluble substances coagulating with $CaSO_4{\cdot}2H_2O$.

3.3. The effect of external electric field on the sedimentation of fine particles

Electrostatic force is suggested as the factors promoting mineral cosedimentation with calcium sulfate dehydrate. Many changes in liquid phase properties, such as pH and ionic strength, vary with the electrostatic force between particles. One of the direct factors is the change in the internal electric field of the liquid phase caused by the external electric field. Fig. 7 is the time-dependent variation in liquid suspended particle number after the application of external electric field. Hence, external electric field affects mineral particle sedimentation.

An electric field affects particle suspension because of the inherent charges of the particles. Sedimentation can be accelerated or slowed down driven by electrophoretic effect. Fig. 7 shows the different charged situations after the combination of minerals with calcium sulfate dehydrate. For quartz, most charges were neutralized after combining with calcium sulfate dehydrate. A weak external electric field effect is found on the sedimentation of quartz-calcium sulfate dehydrate combination, as shown in Fig. 7(a). The sedimentation of quartz itself is significantly influenced by external electric field. When the external electric field is "−120 V/m", the electric field accelerates the sedimentation of quartz particles because of the upward negative electrode and the negatively charged quartz. However, when the external electric field is "+120 V/m", no significant influence is found on particle sedimentation, indicating that gravity has a greater effect on particle sedimentation compared with an external electric field. In Fig. 7(b), potassium feldspar can settle by itself, and external electric field has no influence on sedimentation. After adding calcium sulfate dehydrates, potassium feldspar and calcium sulfate dehydrate co-settle in the first 20 min, which is not affected by external electric field, but the particles increase after 20 min. The growth of particle quantity is a characteristic of nucleus increase during calcium sulfate dehydrate sedimentation, as shown in Fig. 4.

Fig. 7(b) shows that after the cosedimentation of potassium feldspar and calcium sulfate dehydrate, calcium sulfate dehydrate can still break down and release new nucleus, indicating their separable combination. Fig. 7(c) is another situation. Fine kaolin particles easily disperse in water, but sedimentation is accelerated after applying "−120 V/m" external electric field as it is negatively charged. The sedimentation of kaolin is significantly affected by calcium sulfate dehydrate addition, but the variation of particle number during sedimentation with an external electric field is irregular. A possible reason for this observation is the retention of the positive or negative charges of the agglomerated particles so that they are suspended and dispersed under an external electric field. As a contrast, Fig. 7(d) shows the sedimentation of humic acid. Given that humic acid is charged, an external electric field is expected to exert a great effect on it. However, no obvious acceleration of humic acid sedimentation was found with calcium sulfate dehydrate, which demonstrates that calcium sulfate dehydrate does not combine with humic acid, or calcium sulfate dehydrate cannot completely neutralize the charges of humic acid. Fig. 7 indicates that external electric field effectively promotes the sedimentation of silt, clay, and humic acid. Calcium sulfate dehydrate is applicable to the sedimentation of silt and clay, but not to humic acid and feldspar. The application of

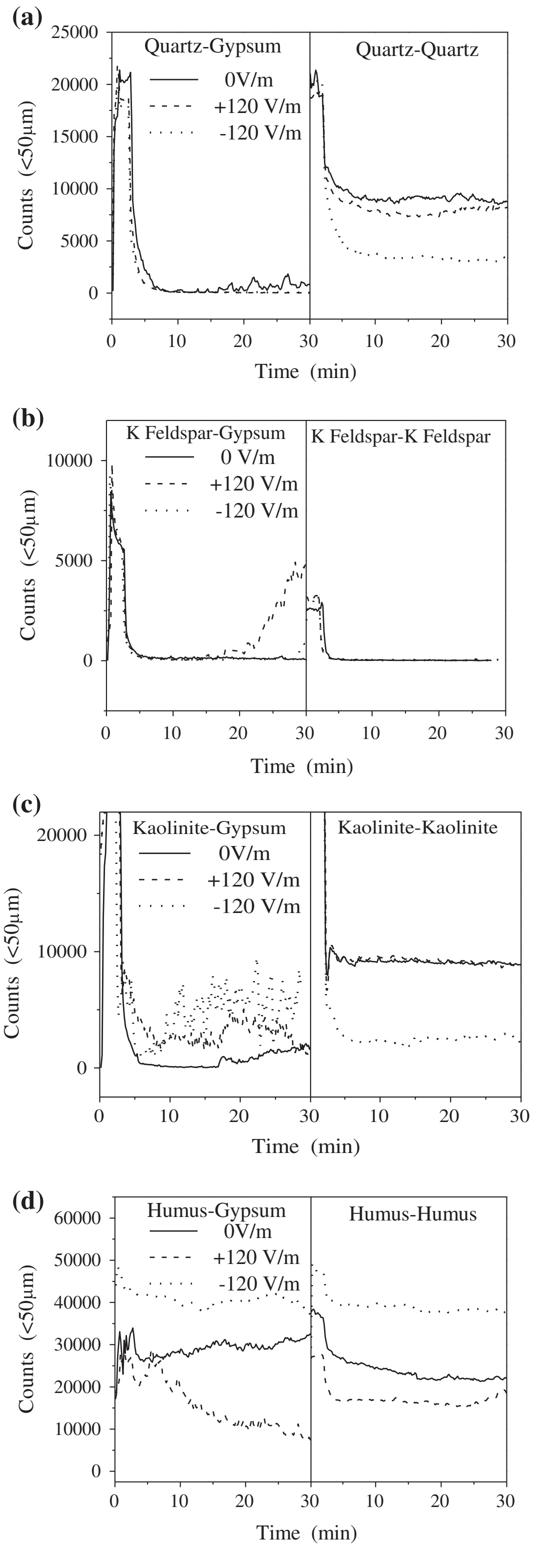


Fig. 7. The sedimentation of insoluble substances affected by external electric field.

electric field does not positively facilitate the sedimentation of calcium sulfate dehydrate and insoluble substance aggregates, but it enhances the dispersion of clay–calcium sulfate dehydrate aggregation.

4. Conclusions

The accelerating effect of calcium sulfate dehydrate on the sedimentation of insoluble substances in water is described in the literature. Experiments also found that calcium sulfate and its hydrous salt can promote the sedimentation of inorganic insoluble substances in water. New nuclei of calcium sulfate dehydrate continue to occur in water. To study the cosedimentation of various insoluble substances and calcium sulfate dehydrate, three substances, silt (quartz), clay (kaolinite and montmorillonite), and feldspar (potassium feldspar and albite) were selected to perform sedimentation experiments together with calcium sulfate dehydrate. The extended DLVO theory calculation shows that the electrostatic force between particles is the key to their cosedimentation with calcium sulfate dehydrate. After the addition of calcium sulfate dehydrate to water with silt or clay, electrostatic forces between particles decrease, leading to their fast sedimentation. However, no significant promotion of electrostatic force was found on the cosedimentation of feldspar and calcium sulfate dehydrate. Calcium sulfate dehydrate does not accelerate the sedimentation of humic acid. The effect of external electric field on sedimentation varies with different mineral particles. The sedimentation of silt, clay, and humic acid is catalyzed; the deposition of calcium sulfate dehydrate and insoluble substances is not promoted, but the dispersion of clay–calcium sulfate dehydrate aggregation is enhanced.

Acknowledgments

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