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Analysis of electrokinetic sedimentation of dredged Welland River sediment

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Abstract

The Welland River is a tributary of the Niagara River. In the late 1980s it was discovered that a section of the Welland River was contaminated with heavy metals as a results of two sewer outfalls that has been used by a steel plant and local industrial and municipal operations for the last 50–60 years. One of the major problems encountered in the treatment of the dredged Welland River sediment is a slow rate of sedimentation due to the large proportion of fine solids in the sediment.

In this study, the results of electrokinetic sedimentation of the Welland River sediment are analyzed based on the principles of gravitational and electrokinetic sedimentation. It was found that the effects of electric field intensity and the initial solid concentration of the suspension are the dominating factors governing the average particle settling velocity, the coefficient of free settling in the free settling stage and the coefficient of sedimentation in the hindered settling stage. The electrokinetic treatment is proven to be effective in terms of increasing the free and hindered settling velocities, reducing the overall sedimentation time and increasing the final solid concentration of the sediment. Thus, electrokinetics can be used to accelerate sedimentation of dilute solid suspensions, such as dredged sediment, wastewater and mine tailings. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Electrokinetics; Electrophoresis; Sedimentation; Contaminated sediment; Solid–liquid separation; Wastewater treatment; Mine tailings; Dewatering

1. Introduction

The restoration and preservation of the biological, chemical and physical quality of the Great Lakes were initiated in 1987 as part of the Great Lakes water quality agreement between Canada and the US. A total of 43 areas of concern (AOC) along the shores and channels of the Great Lakes were identified as regions with impaired ecosystem. The Welland River, a tributary of the Niagara River, represented one of the 17 AOCs in the Canadian side.

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Parts of the river were contaminated with heavy metals, oil and grease. The contamination was originated from two-sewer discharge sites that were used by a steel plant along with other industrial and municipal users in the last 50–60 years. A pilot-scale decontamination program was carried out in 1987, followed by the full-scale dredging operations in 1995 to remove the contaminated sediment. The dredged materials were transported in a slurry form by a flexible pipe system to the treatment facility located over 1 km away. The treatment was intended to separate the solid and contaminants from the slurry in order to treat the water and release it back into the river system and to reduce the volume of solids that may need further treatment or landfill disposal. The treatment facility consisted of coarse vibrating screens, coagulants and mixers to densify the sludge, a high-speed centrifuge to dewater the slurry (which was abandoned later due to ineffectiveness) and two temporary sedimentation lagoons. Due to the large proportion of fine solids, the rate of sedimentation in the lagoons was very slow. Polymer coagulant was added to accelerate the sedimentation with limited success.

An experimental study was initiated to investigate the electrokinetic sedimentation of the Welland River sediment as an alternative solution [1]. In the study, the sedimentation velocity, the coefficient of sedimentation, the final solid content and the sedimentation time were evaluated for the Welland River sediment in a large sedimentation column under various applied voltages and solid concentrations. The study found that the application of a dc electric field increased the final solid concentration by up to 33% and the free settling velocity by up to 110%. The study also found that electrokinetics decreased the coefficient of sedimentation and shortened the overall sedimentation time.

In this paper, the results of the mentioned experimental study are further analyzed and discussed based on the principles of gravitational and electrokinetic sedimentation. This would enhance the understanding of the controlling mechanisms in electrokinetic sedimentation, which may facilitate the design of electrokinetics-assisted sedimentation for dredged sediment, wastewater and mine tailings.

2. Theory of electrokinetic sedimentation

The formation of soils typically goes through two stages; the first stage is known as sedimentation and the second as consolidation. The sedimentation stage consists of free settling and hindered settling. The sedimentation velocity during the free and hindered settling has been discussed in the literature and can be expressed as [2–4]

$$U = \beta u n^{r} \tag{1a}$$

where U (m/s) is the suspension settling velocity, u (m/s) the particle settling velocity, β the coefficient of free settling, n the porosity of the suspension, and r the coefficient of sedimentation.

The settling velocity of a suspension is characterized by the coefficient of free settling (β) in the free settling stage, where the porosity (n) is approximately 1, and hence, Eq. (1a) becomes

$$U = \beta u \tag{1b}$$

The coefficient of free settling (β) represents the statistical average of the settling velocities of particles that defines the mudline, i.e. the face between the clear water and suspended solids. Since the suspension contains various grain sizes and larger particles settle first, the mudline drop represents the settling of particles with finer grain sizes in the suspension. On the other hand, the coefficient of sedimentation (r) controls the settling velocity in the hindered settling stage where the porosity (n) is less than 1 in Eq. (1a).

The coefficients of free settling (β) and sedimentation (r) are functions of the physical, chemical and mineralogical properties of the suspension and can be determined via experiments. The sedimentation parameters in Eq. (1a), i.e. β and r, as affected by electrokinetics on the Welland River sediment are discussed in the following sections.

2.1. Free settling

The free settling of a suspension is observed as particles settle at a constant rate as indicated by Eq. (1b). This occurs in dilute suspensions where the particles are sufficiently far away from each other and from boundaries that contain the suspension. In other words, the interactions between particles are negligible in the free settling stage.

For laminar flow conditions, the classic laws of sedimentation can be used to represent the settling velocity of a single, discrete, non-flocculating particle by gravity [5]:

$$u_{\mathrm{g}} = \frac{g(\rho_{\mathrm{s}} - \rho_{\mathrm{w}})d^2}{18\mu} \tag{2}$$

where u_{g} (m/s) is the particle settling velocity due to gravity, ρ_{s} (Mg/m^3) the density of the particle, ρ_{w} (Mg/m^3) the density of water, g (m/s^2) the acceleration due to gravity, d (m) the diameter of the particle, and μ (kN s/m^2) the viscosity of water.

Since soils consist of varying grain sizes, the particle settling velocity of a soil suspension is not uniform. Therefore, the average particle settling velocity ($\bar{u}_{\mathrm{g}}$) is introduced to evaluate the average particle settling velocity of suspended soil solids, namely,

$$\bar{u}_{\mathrm{g}} = \sum_{i=1}^{N} (f_i - f_{i+1}) \left(\frac{u_{\mathrm{g}(i)} + u_{\mathrm{g}(i+1)}}{2} \right) \tag{3}$$

where f_i is the fraction of the suspension finer than the grain size d_i, and $u_{\mathrm{g}(i)}$ the gravitational settling velocity of an individual particle with the grain size d_i.

Based on the principles of electrochemistry, most surfaces of solids become negatively charged when they are in contact with water. Further, clay particles carry permanent negative charges due to the crystal structure and isomorphous substitution. Therefore, when a dc electric field is applied on a clay suspension, clay particles will move towards the positive electrode (anode). This phenomenon is known as electrophoresis and can be used to accelerate sedimentation of clay suspensions. The velocity of individual particles induced by electrophoresis can be expressed as [3,4,6]

$$u_{\mathrm{ek}} = \frac{\varepsilon_{\mathrm{w}}\zeta}{\mu} E \tag{4}$$

where u_{ek} (m/s) is the particles velocity induced by electrokinetics, ε_{w} (F/m) the permittivity of water, ζ (V) the zeta potential, μ (N s/m^2) the viscosity of water, and E (V/m) is the electric field intensity.

The following assumptions are used in the derivation of Eq. (4).

1. The suspension is dilute so that the porosity is approximately 1, i.e. Eq. (1b) applies.
2. The electrical double layer is much smaller than the particle dimension. The thickness of a diffuse double layer in clay–water–electrolyte systems is in the range of 1–10 nm [7,8]; whereas the size of colloids and clay particles ranges from 0.1 to 5 μm. Therefore, the assumption is valid for clayey suspensions.

Eq. (4) is used to quantify the movement of a soil particle in water by electrokinetics. Unlike the particle settling velocity due to gravity (u_{g}, Eq. (2)), the particle velocity induced by electrokinetics (u_{ek}) is independent of the grain size, as shown in Eq. (4). It should be noted that electrokinetics induced settling becomes negligible in larger non-clay particles because the negative charge on particle surfaces is small so that the zeta potential (ζ) is negligible, and the grain size is large, so that gravitational settling is predominant. This point will be further illustrated in the next sections.

The overall particle settling velocity induced by gravity and electrokinetics is the summation of Eqs. (2) and (4), i.e.

$$u = u_{\mathrm{g}} + u_{\mathrm{ek}} \tag{5}$$

Eq. (5) indicates that by proper arrangement of the electric field configuration, particles in a suspension can settle at a higher velocity by imposing an external dc electric field. The average particle settling velocity due to gravity and electrokinetics ($\bar{u}$) is given by combining Eqs. (3) and (4) as

$$\bar{u} = \sum_{i=1}^{N} (f_i - f_{i+1}) \left(\frac{u_{\mathrm{g}(i)} + u_{\mathrm{g}(i+1)}}{2} + u_{\mathrm{ek}} \right) = \bar{u}_{\mathrm{g}} + u_{\mathrm{ek}} \tag{6}$$

Consider a suspension containing grain sizes ranging primarily from silt ($5\ \mu\mathrm{m} < d < 75\ \mu\mathrm{m}$) to clay ($d < 5\ \mu\mathrm{m}$). The sedimentation velocity is measured as the rate of mudline drop with time [1]. The free settling process is represented by the linear drop of the mudline with time when the porosity of the suspension (n) is approximately equal to 1. Therefore, by substituting the average particle settling velocity ($\bar{u}$) in Eq. (6) into Eq. (1a), we obtain

$$U_{\mathrm{f}} = \beta \bar{u} \tag{7}$$

where U_{f} is the free settling velocity of a dilute suspension.

Eq. (7) is the governing equation for electrokinetics enhanced free settling, in which $\bar{u}$ represents the combined average particle settling velocity induced by gravity and electrokinetics. Since the free settling velocity (U_{f}) is measured by the drop of mudline with time, it represents the settling of the finer particles with the lower settling velocity, as discussed earlier. Therefore, $\bar{u}$ is averaged over the fine particles, in particular, over clay sized particles with the grain size $d < 5\ \mu\mathrm{m}$.

In addition to the increase in the particle velocity by electrokinetics, the changes in the coefficient of free settling (β) is another indicator of the effect of electrokinetics in the settling process. The change of the coefficient by the application of a dc electric field indicates the acceleration of the settling velocity of finer particles, which can be evaluated experimentally by using the results of a sedimentation column test.

2.2. Hindered settling

As the settling process continues with time, the solid concentration increases in the suspension, the porosity decreases and so does the sedimentation velocity, as described in Eq. (1a). This represents the hindered settling process. In this case, the porosity of the suspension is less than 1 and $U = U_\mathrm{h}$ in Eq. (1a), where U_h is the hindered settling velocity. When the suspension includes particles of various sizes, we may substitute the average particle settling velocity ($\bar{u}$) from Eq. (6) into Eq. (1a) and obtain

$$U_\mathrm{h} = \beta \bar{u} n^r = U_\mathrm{f} n^r \tag{8}$$

Eq. (8) can be re-expressed as

$$\log\left(\frac{U_\mathrm{h}}{U_\mathrm{f}}\right) = r \log(n) \tag{9}$$

The effect of applying a dc electric field to the clay suspension can be represented by the change in the sedimentation coefficient, i.e.

$$r = r_\mathrm{g} - \Delta r \tag{10}$$

where r_g is the coefficient of sedimentation by gravity and Δr the change in the coefficient of sedimentation by electrokinetics. The physical meaning of Δr in Eq. (10) is clearly shown in Eq. (8), i.e. it causes the decrease in the coefficient of sedimentation by electrokinetics and leads to the increase in the hindered settling velocity at a specific porosity.

Eq. (9) indicates that the hindered settling process is controlled by the coefficient of sedimentation and the porosity of the suspension. It is apparent from the equation that the hindered settling velocity decreases as the porosity decreases with time. When the settling velocity approaches zero, the hindered settling process ends and then the consolidation process starts, which is well known in soil mechanics.

2.3. Evaluation of electrokinetics enhanced settling process

Based on the analysis in the previous sections, the electrokinetics sedimentation is evaluated through the following steps.

1. The gain size distribution of the suspension is identified and plotted.
2. Eq. (2) is used to evaluate the particle settling velocity induced by gravity (u_g) for the various grain sizes in the suspension.
3. The average particle settling velocity of the suspension under gravity ($\bar{u}_\mathrm{g}$) is evaluated from Eq. (3), which is averaged over clay sized particles ($d < 5\,\mu\mathrm{m}$).
4. Knowing the zeta potential (ζ) of the clay sized particles from measurement and the applied electric field intensity (E), Eq. (4) is used to calculate the particle velocity induced by electrokinetics (u_ek).

5. The average particle settling velocity due to gravity and electrokinetics ($\bar{u}$) is calculated from Eq. (6).
6. Knowing the free settling velocity from the experiment, Eq. (8) is used to evaluate the coefficient of free settling (β) in the gravitational and electrokinetic sedimentation processes.
7. The change in the coefficient of settling (β) along with the increase in the particle velocity (u_{ek} in Eq. (6)) reflects the effects of electrokinetics in the free settling stage.
8. The coefficient of sedimentation (r) is obtained from experimental results on gravitational and electrokinetics-enhanced settling tests.
9. Eqs. (8)–(10) are used to estimate the change in the coefficient of sedimentation due to electrokinetics (Δr).

In the following sections, the results of electrokinetic sedimentation tests on the Welland River sediment are analyzed and discussed using the above outlines.

3. Experimental program

3.1. Sediment properties

The sediment used in this study was recovered from two sedimentation lagoons dredged from the Welland River. The sediment may be classified as a low plasticity clayey silt consisting of 4% sand, 61% silt and 35% clay sized grains [1]. Atterberg limits tests indicated that the sediment has a low plasticity. The X-ray diffraction and the chemical analysis showed that chlorite, illite-mica and quartz are the dominant minerals of the sediment accounting for approximately 75% of the solids. The rest of the sediment is primarily comprised of carbonates and organics with small amount of feldspar. Table 1 summaries the properties of the Welland sediment [1].

Table 1
Properties of Welland River sediment

Geotechnical properties	Value	Pore fluid chemistry	Value	Mineralogy (%)	Value	Contaminants concentration in soil (ppm)	Value
Liquid limit (%)	41.3	pH	7.5	Chlorite	$\sim$22	Oil + grease	23900
Plastic limit (%)	28.2	Conductivity (mS/m)	31	Illite-mica	$\sim$25	Co	40
Plasticity index (%)	13.1	Na^+ (mg/l)	6.2	Quartz	$\sim$27	Cr	2563
Sand (%)	4	K^+ (mg/l)	1.4	Feldspar	$\sim$3	Cu	371
Silt (%)	61	Ca^+ (mg/l)	35.8	Calcite	$\sim$10	Fe	83845
Clay (%)	35	Mg^{2+} (mg/l)	7.4	Dolomite	$\sim$6	Mn	1021
Specific gravity	2.85	Cl^- (mg/l)	17	Organic content	$\sim$7	Ni	1024
Specific surface (m^2/g)	16	$SO_4{}^{2-}$ (mg/l)	46.5			Pb	239
CEC (meq/100 g)	13	$NO_3{}^-$ (mg/l)	10			Zn	286
Zeta potential (mV)	−16	$HCO_3{}^-$ (mg/l)	35				

3.2. Experimental apparatus

A brief description of the sedimentation column and the experimental procedure are outlined in this section. A detailed description can be found in [1]. Two identical sedimentation columns, 1 m high and 20 cm i.d., were designed and constructed from a 6 mm thick Plexiglass tube. Fig. 1 shows a photograph of the sedimentation column [1]. One column was used for electrokinetic sedimentation and the other for gravitational sedimentation (control). The column was designed to be long enough (1 m) to allow for accurate observation and measurement of the settling velocity of suspensions during the free and hindered settling stages. The diameter of the column (20 cm) was designed to be wide enough to minimize the boundary effect on the settling process. The electrodes, 20 cm in diameter, were made of 1 mm thick flexible graphite sheet and placed in parallel at the top and bottom of the column with 1 m spacing to generate a uniform electric field. During electrokinetics tests, the bottom electrode is connected to the positive terminal of the power supply as the anode, and the top electrode is connected to the negative terminal and grounding system as the

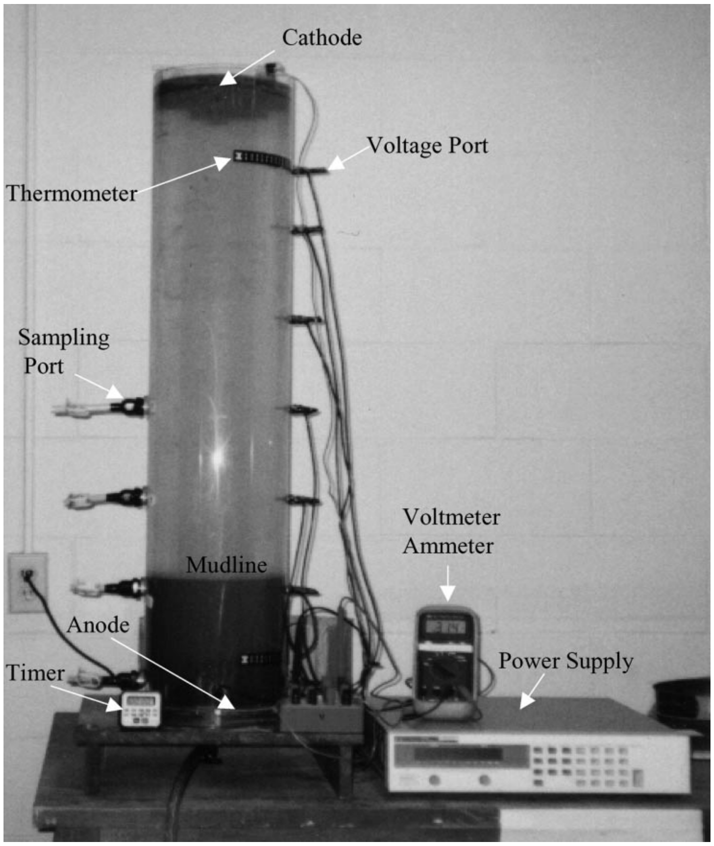

Fig. 1. Photograph of the sedimentation column.

cathode. Therefore, clay particles with negative charges will be expelled from the top of the sedimentation column and move towards the bottom (anode), thus, inducing accelerated sedimentation.

3.3. Experimental procedure

The slurry used in the tests was prepared by mixing predetermined quantities of dry soil and water to form a suspension of a known initial solid concentration (% mass/mass). The slurry was then poured into the two identical sedimentation columns for control and electrokinetics tests that were performed simultaneously. The electric field was provided by a dc power supply with a capacity of 150 V and 1 A (Hewlett–Packard 6545A-J05) through the top cathode and bottom anode at 1m apart. The electric field intensity (E) can be calculated from

$$E\ (\mathrm{V/m}) = \frac{V_0}{1},$$

where V_0 is the applied voltage. The test results discussed in this paper are divided into two groups.

1. *Test numbers 1–5*: investigate the effect of initial solid concentration for tests conducted with a constant electric field intensity of 150 V/m. The corresponding current densities ranged from 5.9 to 9.1 A/m^2. The current density in each of the tests remained approximately constant due to the relatively short testing period [1].
2. *Test numbers 3, 6, 7 and 8*: investigate the effect of applied electric field intensity under a constant initial solid concentration of 14.4% mass/mass.

It is worthwhile to mention that in an electrokinetic sedimentation process, a pH gradient develops across the sedimentation column with time, i.e. the pH increases at the cathode (top) and decreases at the anode (bottom). However, the short testing period of the test series (less than 2 h) and the dilution effect of the suspension (especially at the cathode) considerably reduced the pH gradient across the column. The results of the tests are summarized in Table 2 and discussed in Section 4.

4. Analysis and discussion

4.1. Particle settling velocity

The grain size distribution of the Welland River sediment recovered from a sedimentation lagoon is shown in Fig. 2. About 96% of particles in the sediment have silt or clay sizes. Using Eq. (2), the particle settling velocity by gravity (u_g) is calculated and presented in Fig. 3 for the Welland River sediment. Fig. 3 also plots the particle velocity due to electrokinetics (u_{ek}) at the applied electric field intensity of 150 V/m, calculated from Eq. (4) after determining the zeta potential of the clay particles in the sediment (-16 mV) using a zeta potential analyzer (Brookhaven Instruments Corporation, NY). The overall particle settling velocity due to the combined effects of gravity and electrokinetics (u) calculated from Eq. (5) is also

Table 2
Summary of experimental results[a]

Test number	Description	Initial solid concentration (%)	E (V/m)	U_f (cm/min)	β	r_g	r	Δr	Final solid concentration (%)	Sedimentation time (min)
1C	Control	11.4	0	3.9	92.9	18.8	–	–	60	34
1E	EK	11.4	150	7.8	150	–	12.7	6.1	62	27
2C	Control	13.1	0	2.1	50.0	21.6	–	–	47	82
2E	EK	13.1	150	4.3	82.7	–	13.1	8.5	58	42
3C	Control	14.4	0	1.7	40.5	10.2	–	–	39	103
3E	EK	14.4	150	3.2	61.5	–	7.6	2.6	51	50
4C	Control	15.1	0	1.5	35.7	16.3	–	–	40	103
4E	EK	15.1	150	1.9	36.5	–	13.7	2.6	53	70
5C	Control	17.0	0	0.9	21.4	18.2	–	–	49	115
5E	EK	17.0	150	1.0	19.2	–	15.2	3.0	44	133
6E	EK	14.4	40	2.0	44.7	10.2	9.5	0.7	44	90
7E	EK	14.4	80	2.1	44.3	10.2	8.7	1.5	46	79
8E	EK	14.4	115	2.4	48.2	10.2	7.9	2.3	48	70

[a] EK: electrokinetic test; E: applied electric field intensity; U_f: free settling velocity; β: coefficient of free settling; r_g: coefficient of sedimentation by gravity; r: coefficient of sedimentation by gravity and electrokinetics; Δr: change in the coefficient of sedimentation due to electrokinetics.

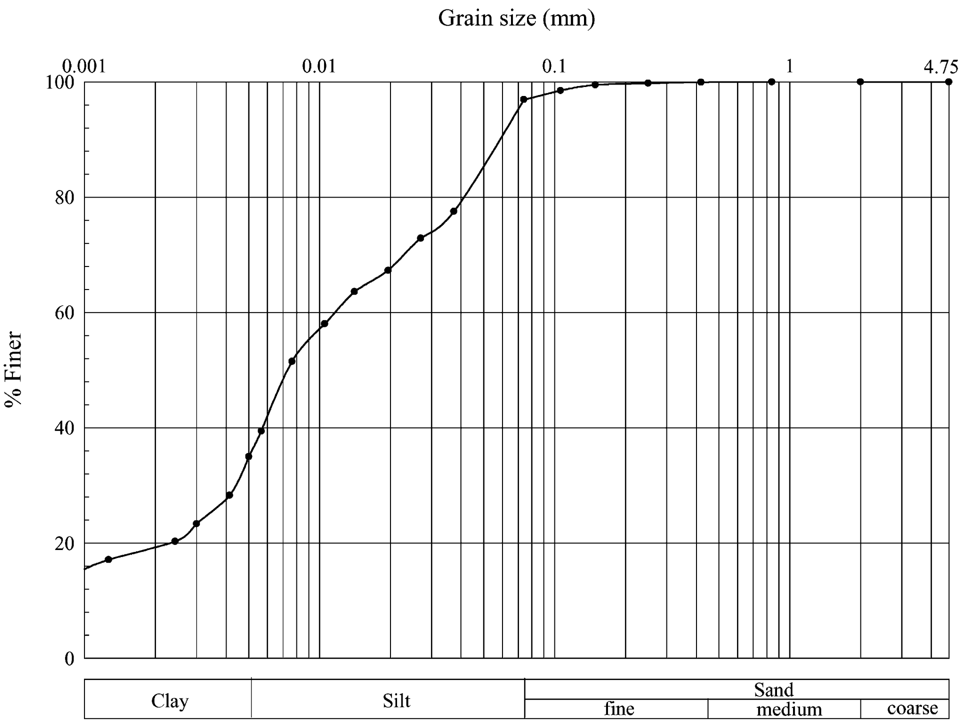

Fig. 2. Grain size distribution of the Welland River sediment.

presented in Fig. 3. The figure clearly illustrates three zones for the overall particle settling velocity (u).

- *Zone 1 in which the grain size is less than 1 μm*: the particle velocity induced by electrokinetics (u_{ek}) at electric field intensity of 150 V/m contributes to more than 64% of the overall particle settling velocity. The particles in this zone fit the grain size of colloids and represent typical characteristics of colloidal suspensions, namely, the surface forces dominate the particle movement and the gravitational force is insignificant.
- *Zone 2, in which the grain sizes range between 1 and 5 μm*: both gravitational and electrokinetic forces play a significant role in the settling process of the particles. The overall settling velocity of the particles is the summation of the gravitational and electrokinetic settling velocities. Most clay particles fit into this range of grain sizes.
- *Zone 3, in which the grain size is larger than 5 μm*: the gravitational forces predominantly control the overall particle settling velocity, whereas the effect of electrokinetics is negligible. In the meantime, sedimentation is expected to complete in a short time period due to the large grain sizes, as described in Eq. (3). Sand and silt particles fit into this zone.

It may be anticipated based on the above analysis that electrokinetics will primarily accelerate sedimentation for particles in Zones 1 and 2, i.e. particles with grain sizes smaller than 5 μm. For the Welland River sediment this represents about 35% of the sediment.

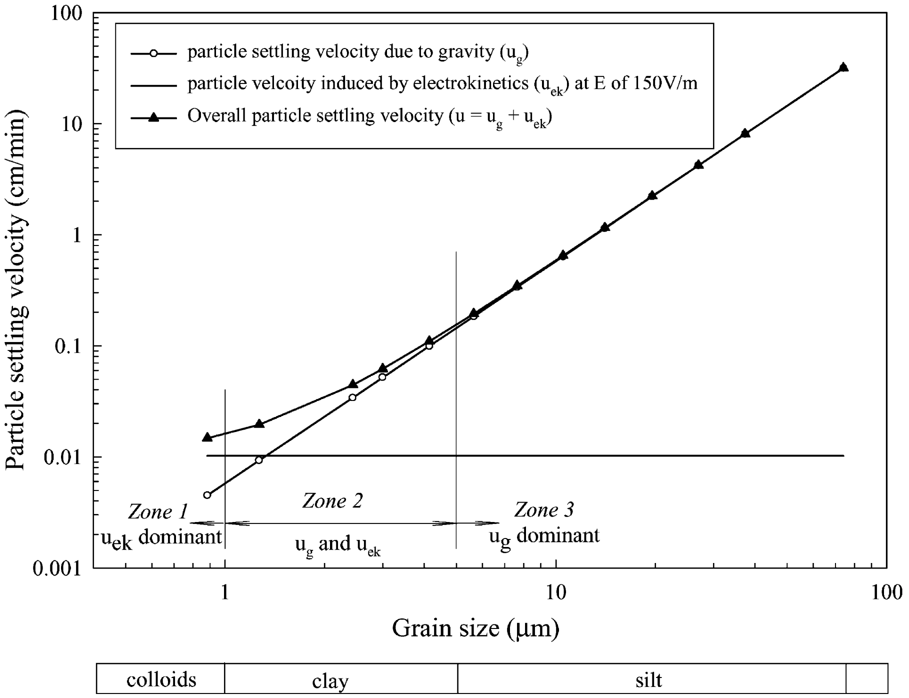

Fig. 3. Particle settling velocity vs. the grain size.

Fig. 4 shows the sediment fractions versus the gravitational particle settling velocity (u_g) and the overall particle settling velocity induced by gravity and electrokinetics (u). The former is calculated from Eq. (2) and the latter from Eq. (5), based on the grain size distribution shown in Fig. 2. The average particle velocities are then calculated by Eqs. (3) and (6), for the gravitational and electrokinetics settling, respectively. It is obvious that the average settling velocity is represented by the area enclosed by the curve and the vertical axis in Fig. 4.

It has been discussed in the previous section that the drop of the mudline measured in the tests represents the free settling velocity of the suspension (U_f) and is primarily attributed to the settling of clay sized particles since larger particles settle much faster. Therefore, the average particle gravitational settling velocity ($\bar{u}_g$, Eq. (3)) was calculated as the average velocity of particles with sizes less than 5 μm (constitutes about 35% of the sediment) and found to be 0.042 cm/min. The average particle settling velocity due to gravity and electrokinetics ($\bar{u}$, Eq. (6)) was also evaluated and found to be 0.052 cm/min, which implies a 23.8% increase compared to the average gravitational particle settling velocity, as shown in Fig. 5. To further illustrate, Fig. 5 presents the average particle settling velocity due to gravity ($\bar{u}_g$) and due to the combination of gravity and electrokinetics ($\bar{u}$) versus the maximum grain size over which the average settling velocity is calculated. It is shown clearly in Fig. 5 that electrokinetics significantly increases the particle settling velocity

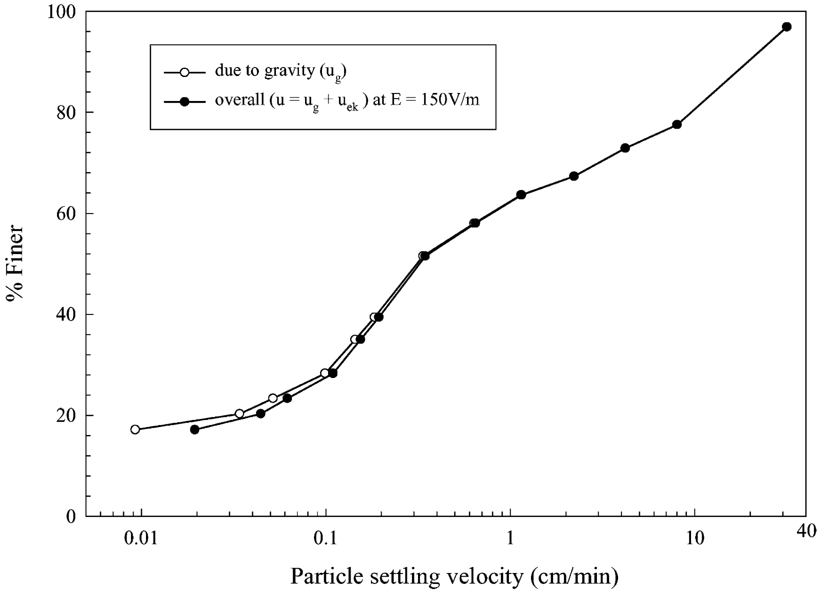

Fig. 4. Particle settling velocity vs. the percentage of Welland River sediment.

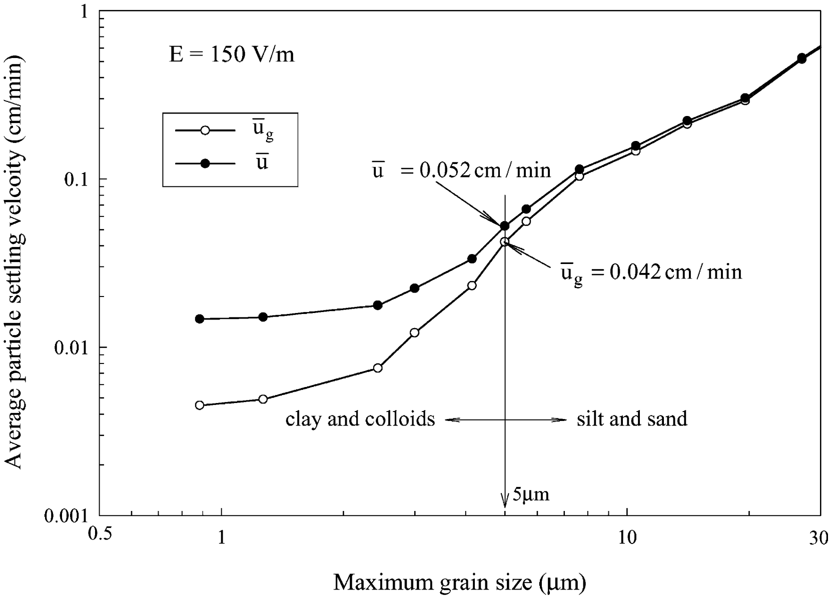

Fig. 5. Average particle sediment velocity vs. the maximum grain size.

only for clay sized particles in the suspension. The effect of electrokinetics during the free and hindered settling processes is discussed in the following sections.

4.2. Free settling

The free settling velocity (U_f) of the Welland River sediment suspension is a function of the solid concentration for both the cases of gravitational and electrokinetics settling, as shown in Fig. 6(a), which was obtained through measuring the mudline drop with time. The results of the tests are summarized in Table 2. The coefficient of free settling (β) is obtained from Eq. (7) using the average particle settling velocity ($\bar{u}$) over the clay sized particles, as shown in Fig. 6(b). The Following can be observed from Fig. 6(b).

- In general, the coefficient of free settling (β) decreases with the increasing solid concentration of the suspension in both gravitational (control) and electrokinetics tests.
- The application of a dc electric field significantly increases the coefficient of free settling (β) at lower solid concentrations, i.e. when the solid concentration is lower than 15%. For example, β is 150 in the electrokinetic tests compared to 92.9 in the control test at the initial solid concentration of 11.4%, which represent an increase of 61.5%.
- The coefficient of free settling (β) is no longer affected by the application of a dc electric field when the initial solid concentration is greater than 15%. As shown in Fig. 6(a) and (b), electrokinetics at initial solid concentrations more than 15% generated slight increase in the free settling velocity which is solely attributed to the increase in the average particle settling while β remains approximately the same.

The results indicate that electrokinetics can be used to accelerate sedimentation of dilute suspensions, such as the sedimentation of wastewater treatment tanks, mine tailings discharge, etc.

The effect of electrokinetics to the free settling of the Welland River sediment suspensions is further studied through Test numbers 3, 6, 7 and 8, in which the variable was the applied electric field intensity (E) while the initial solid concentration of the suspensions was kept constant at 14.4%.

Fig. 7(a) presents the measured free settling velocity (U_f) as a function of the electric field intensity (E) where $E = 0$ represents the control test. The coefficient of free settling (β) is calculated from Eq. (7), knowing the settling velocities at the various electric field intensities in which the average particle settling velocity is calculated from Eq. (6), i.e.

$$\bar{u} = \bar{u}_g + u_{ek} = 0.042 + \frac{\varepsilon_w \zeta}{\mu} E \tag{11}$$

For the Welland River sediment, the zeta potential is −16 mV (Table 1). The average particle settling velocity ($\bar{u}$) is proportional to the applied electric field intensity (E), which is calculated from Eq. (11) and labeled in Fig. 7(b) of each of the electric field intensity applied.

It is noted from Fig. 7(b) that the coefficient of free settling (β) increases with the applied electric field intensity (E) in a non-linear trend. It remains fairly constant up to $E = 80$ V/m, then increases significantly with further increasing in the electric field intensity. This is attributed to the stronger electrostatic forces imposed on suspended particles that overcome interparticles repulsions of finer (colloidal) particles.

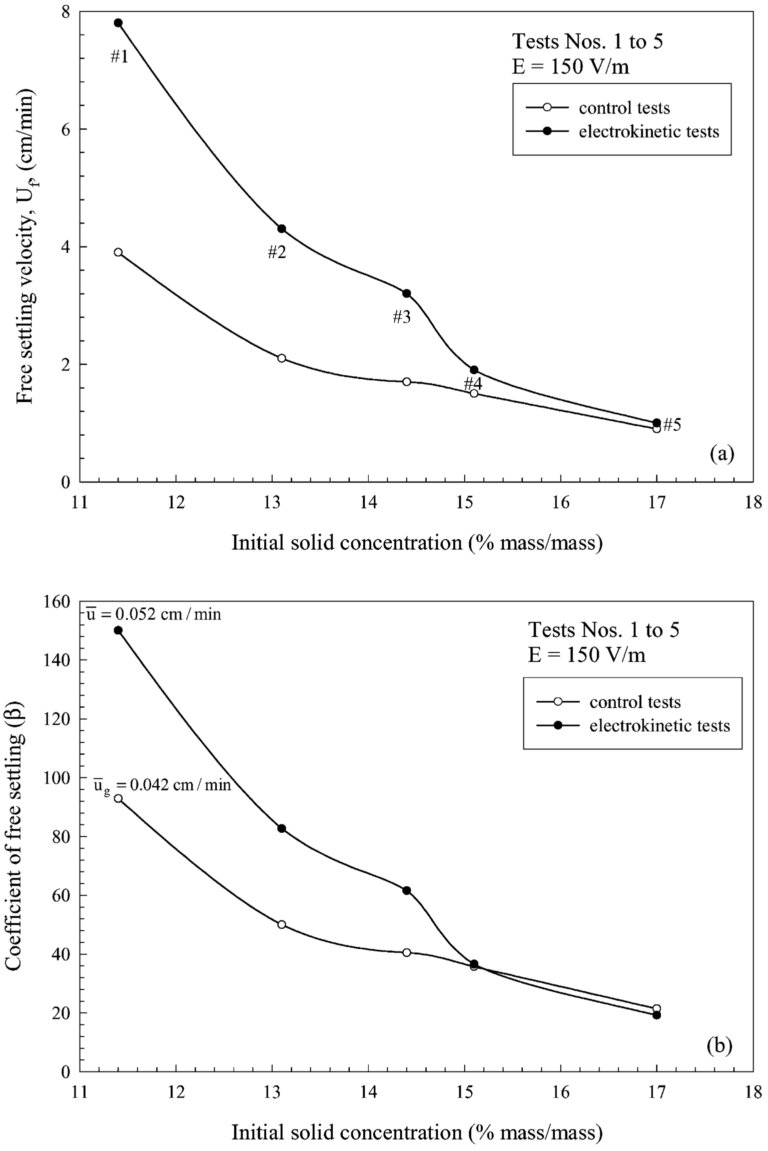

Fig. 6. (a) Free settling velocity vs. the initial solid concentration of the suspensions; (b) coefficient of free settling vs. the initial solid concentration of the suspensions.

4.3. Hindered settling

The effect of electrokinetics to the hindered process as related to the initial solid concentration is examined through Test numbers 1–5. The coefficient of sedimentation (r) is calculated for the control and electrokinetic tests from Eq. (9) and presented in Fig. 8. The

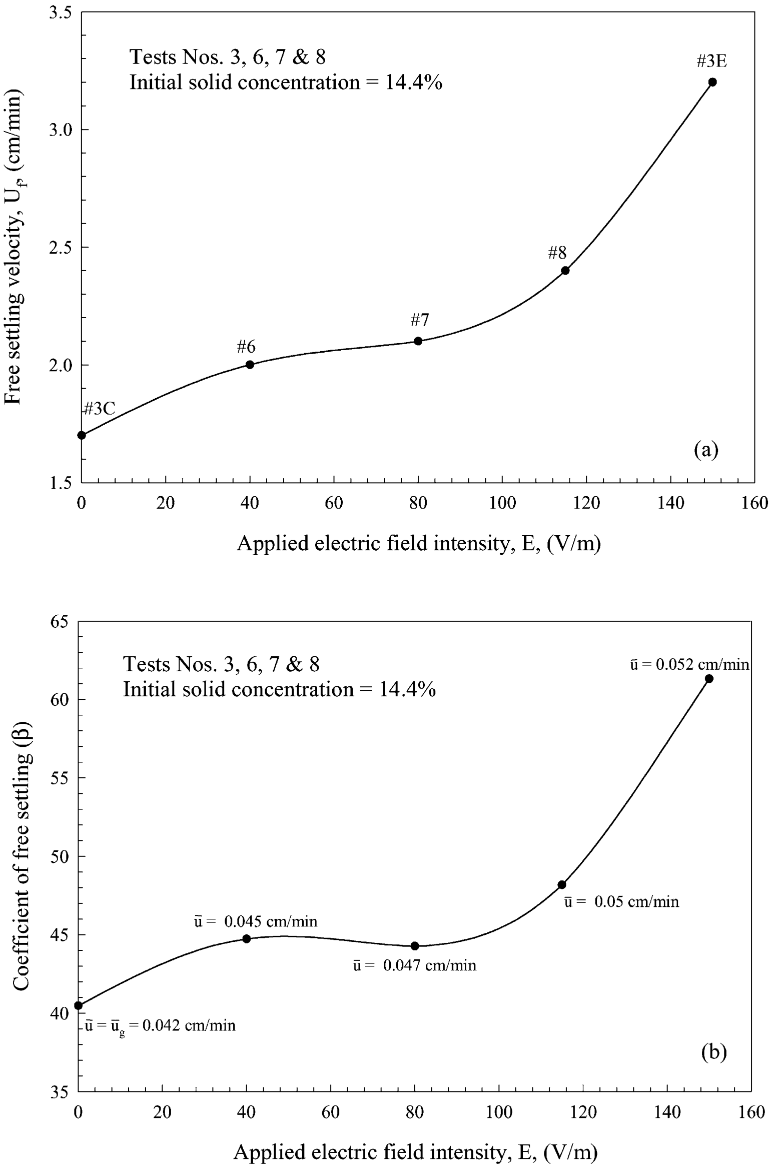

Fig. 7. (a) Free settling velocity vs. applied electric field intensity; (b) coefficient of free settling vs. applied electric field intensity.

decrease in the coefficient of sedimentation in electrokinetic settling process (Δr) evaluated from Eq. (10) is also presented in Fig. 8. Note that a lower coefficient of sedimentation in electrokinetics settling, r, as defined in Eq. (10), corresponds to a higher hindered settling velocity (U_{h}) as described by Eq. (8), as the porosity is less than 1. In other words, a large

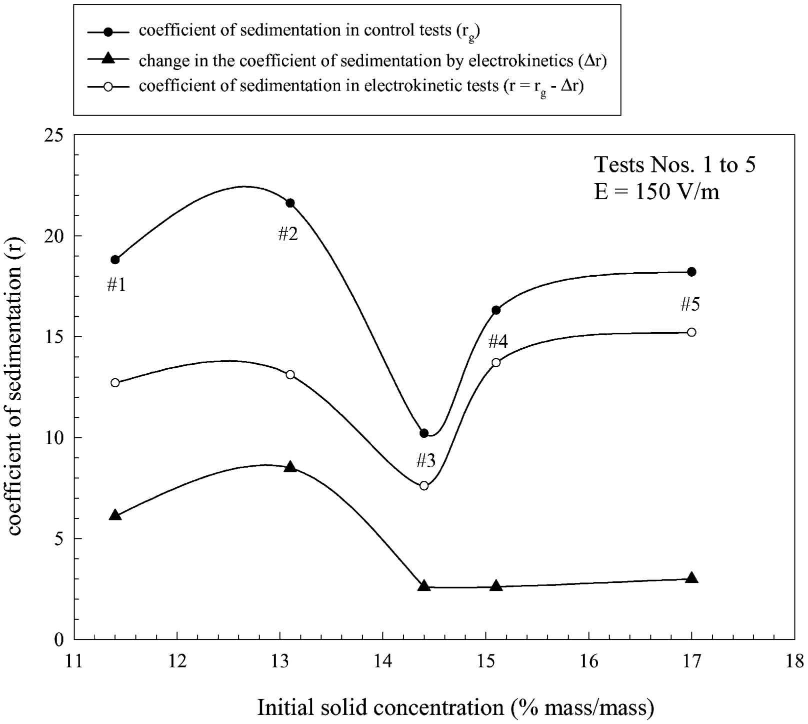

Fig. 8. Coefficient of sedimentation vs. initial solid concentration of the suspensions.

decrease in the coefficient of sedimentation (Δr) implies that electrokinetics generated greater acceleration to the settling process.

The following can be observed from Fig. 8.

- There is a minimum coefficient of sedimentation at the initial solid concentration of 14.4% in both gravitational and electrokinetic settling tests for the Welland River sediment. This means that the hindered settling velocity decreases least rapidly with the porosity at this initial solid concentration for the Welland River sediment suspension.
- The coefficient of sedimentation was found to be a function of the solid concentration with values between 10.2 and 21.6 in the control tests, which are comparable to the range of 4.5–29.2 tested on silts by McRoberts and Nixon [2].
- At all solid concentrations tested, electrokinetics reduced the coefficient of sedimentation, leading to the increase in the hindered settling velocity of the suspension.
- The effect of electrokinetics as evaluated by the change in the coefficient of sedimentation (Δr) is most significant in suspensions of low solid concentrations. In the Welland River sediment suspensions, the change in the coefficient of sedimentation is most significant at initial solid concentrations of 11.4 and 13.1%, whereas it started to decrease at the solid concentration of 14.4% and remains fairly constant at higher solid concentrations.

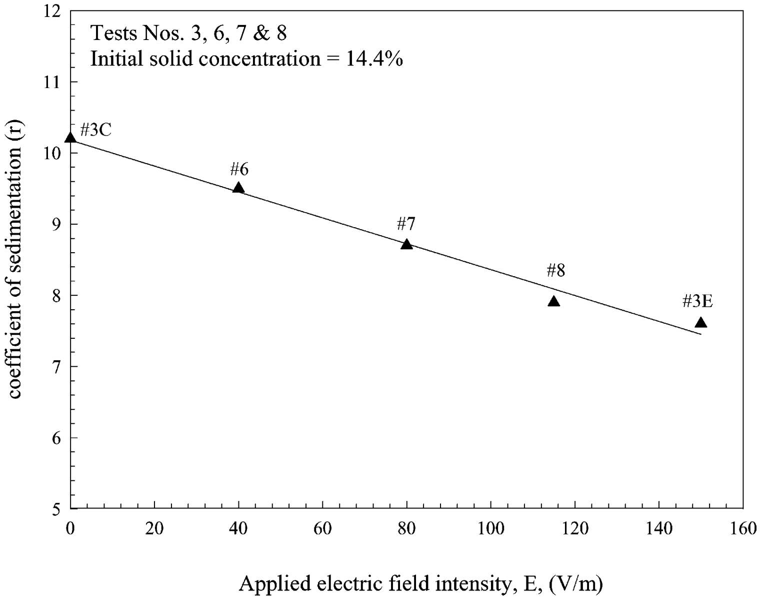

Fig. 9. Coefficient of sedimentation vs. applied electric field intensity.

By comparing the effects of electrokinetics in a sedimentation process during the free settling stage (Fig. 6(a) and (b)) and the hindered settling stage (Fig. 8), it may be observed that electrokinetics increases the settling velocity of suspensions of lower initial solid concentrations (<15%) at both settling stages. At higher solid concentrations (>15%), the primarily function of electrokinetics is to increase the hindered settling velocity, represented by the decrease in the coefficient of sedimentation (Δr), whereas the free settling velocity is not significantly affected.

The effects of electrokinetics on the hindered settling process is further examined in terms of the applied electric field intensity, as shown in Fig. 9, in which all the suspensions have the same initial solid concentration of 14.4%. It is clear from the figure that the coefficient of sedimentation (r) decreases linearly with the applied electric field intensity. Thus, the application of a stronger electric field would lead to a higher hindered settling velocity, shorter sedimentation time and higher final solid concentration. It should be noted that the maximum electric field intensity used in the study (150 V/m) can be readily achieved in field applications.

The final solid concentration and the overall sedimentation time for the tests conducted are summarized in Table 2. It is apparent from the results that the final solid concentrations of all the suspensions tested increased due to the application of a dc electric field as compared to the control tests. The increases are functions of both the initial solid concentration and the applied electric field intensity. The maximum increases of over 30% were achieved at tests conducted with initial solid concentrations of 14.4% (Test number 3E) and 15.1% (Test number 4E). It is also clear from the results in Table 2 that the increase in the final solid concentration is proportional to the applied electric field, which is consistent with the analysis in the free and hindered settling processes.

The results in Table 2 show that the sedimentation time was reduced by the application of a dc field in all the tests conducted. The largest reduction of 53 min (from 103 min in the control test to 50 in the electrokinetic test) was reported for Test number 3, in which the initial solid concentration 14.4%. Further the overall sedimentation time decreased with the increasing applied electric field intensity. It can be concluded that the application of a dc electric field enhances the sedimentation process by achieving the two goals, namely, increasing the final solid concentration and decreasing the sedimentation time.

5. Conclusions

The effects of electrokinetic sedimentation of the sediment dredged from the Welland River are studied in terms of free and hindered settling processes. In the free settling stage the effects were evaluated through the average particle settling velocity ($\bar{u}$) and the coefficient of free settling (β), while in the hindered settling stage the effects were represented by the change in the coefficient of sedimentation (Δr). The following conclusions were reached from the study.

1. The application of a dc electric field accelerates primarily the settling velocity of clay sized particles with grain sizes less than 5 μm. The effect can be quantified by the average particle settling velocity ($\bar{u}$) introduced in this study.
2. The coefficient of free settling (β) is used to evaluate the effects of electrokinetics to the free settling of clay suspensions. It is found that the coefficient of free settling is a function of the initial solid concentration of the suspension and the applied electric field intensity. It is also concluded that when the initial solid concentration of the clay suspension is higher than a critical value, the coefficient of free settling is no longer affected by electrokinetics.
3. The coefficient of sedimentation (r) is used to evaluate the effect of electrokinetics to the hindered settling of clay suspensions. It is found that electrokinetics induces a decrease in the coefficient of sedimentation, leading to faster sedimentation velocity and shorter sedimentation time. The change of the coefficient of sedimentation (Δr) is also a function of the initial solid concentration and the applied electric field intensity. An optimal initial solid concentration (14.4%) is observed for the Welland River sediment, at which the coefficient of sedimentation reaches the minimum value (7.6). On the other hand the coefficient of sedimentation decreases linearly with the applied electric field intensity, indicating a higher applied voltage would generate faster sedimentation of the suspension.

As evidenced from this study, electrokinetics can serve as a viable tool to accelerate the settling of dilute fine suspensions in applications including dewatering of dredged sediment, wastewater and mine tailings.

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