Note

Effects of Container Diameter and Volume Fraction on the Sedimentation Process of Flocculated Clay Suspensions

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We studied the dependence of sedimentation process in a flocculated kaolinite suspension on the diameter of cylindrical container in the measurement and volume fraction of clay in the suspension. The obtained results were as follows. The constant velocity in the slow settling process depends on the container diameter. In large containers ($D=21.3, 28.2, 63.5$ mm), it becomes larger as the container diameter increase. This phenomenon can be explained on the basis of a theory focusing on wall stress. However, there exists hardly difference in settling velocity among the small containers ($D<13.9$ mm) and the very slow sedimentation regardless of the container diameter causes. It is guessed that this phenomenon occurs by the flow which doesn't depend on the container diameter. On the other hand, the maximum settling velocity in the rapid settling process was almost constant regardless of container diameter. From this result, it became clear that the container diameter did not affect on the rapid settling process.

Key Words: Sedimentation / Settling velocity / Container diameter / Wall stress / Clay suspension

1. INTRODUCTION

Sedimentation experiments are often carried out to examine the effects of flocculants, pH, and salt concentrations on flocculation behaviors of clay-water suspensions. In the sedimentation experiments, one estimates the influence of ionic strength, ion species, and clay concentrations on the sediment volume, generally being left for 24 hours, and/or the settling types of flocculated suspensions.¹⁻⁴⁾ The classical sedimentation experiments are useful for the qualitative judgment whether the suspension is stable or not. Nevertheless, the quantitative evaluation of sedimentation phenomena is still unclear due to the lack of understanding on the mechanism of sedimentation process.

Richardson & Zaki⁵⁾ measured the rate of group settling of uniform rigid particles at higher particle concentrations under the condition where hydrodynamic similarity was satisfied and the sedimentation was hindered by the particle-particle interaction. Then they proposed an empirical equation that describes the rate of sedimentation of the boundary between the settling suspension and the clear supernatant as a function of the volume fraction of particles. Michaels & Bolger⁶⁾ successfully applied the Richardson & Zaki equation to the analysis of sedimentation of flocculated kaolinite suspensions

by using the idea of effective volume fraction of flocs, aggregates of primary particles, that consist of immobile water and the particles. The results of these studies enable us to treat quantitatively complicated sedimentation phenomena of flocculated suspension. Michaels & Bolger concluded that the wall effect on sedimentation is negligible from the measurements using the large cylinder with 65 mm diameter and 1000 mm height.

Many sedimentation experiments were carried out in beakers and measuring cylinders, whose diameters were smaller than those used by Michaels & Bolger. So, it was possible that the wall effect was not negligible in some of previous investigations. Unless the effect of the wall of containers on sedimentation is negligible, the rate of sedimentation probably depends on the diameter of used containers. So far, the effect of wall on the sedimentation rate of a floc has been studied.⁷⁻¹⁰⁾ On the contrary, few studies have been reported on how the shear resistance by the wall of a container affects the group settling of flocs (so called soft matters).

In the present study, we investigated the dependence of the settling properties of flocculated clay-water suspensions on the diameter of containers by means of a three dimensional reading microscopy, by which we can measure the change of the height of the boundary between supernatant and settling sediment with accuracy of 1/100 mm.

2. MATERIALS AND EXPERIMENTAL METHOD

2.1 Materials

We used pure Na-saturated kaolinite clay particles (Iriki, Japan), which were prepared by repeatedly washing the clay particles against 1 mol/L NaCl solutions. After the washing treatment, excess salt in the bulk solution of the suspension was removed by repeating centrifugation until the salt concentration of the suspension became less than 10^{-4} mol/L. Then, particles larger than 3 μm were removed by sedimentation. The kaolinite particles were flocculated at pH 10.0 by increasing NaCl concentration of the suspension to 0.2 mol/L.

2.2 Measurement of Sedimentation Rate

Experiments were performed in a temperature-controlled room at 25 °C. The solid volume fraction of suspensions ranged from 0.2 % to 0.8 %. The diameters of sedimentation cylinders used in this study were 9.40, 11.05, 13.90, 21.25, 28.20, and 63.5 mm. Just before a sedimentation experiment, the suspension in the sedimentation cylinder was sonicated five minutes and followed by end-over-end rotation 20 times. Then, the cylinder was left stand and the temporal change of the height of the boundary between the supernatant and the settling sediment was measured from magnified pictures on a display obtained through a video camera equipped on a three dimensional reading microscopy.¹¹⁾ This setup allows us to obtain the height with precision of 0.01 mm. The height was recorded every 30 seconds, and thus the temporal variation of the height was investigated in detail. By using the measurements procedure described above, we can perform the precise measurement of very slow sedimentation velocity and the detailed observation of the suspension during sedimentation.

3. EXPERIMENTAL RESULTS

The temporal variations of the sediment height of a flocculated kaolinite suspension, measured in the cylinder of 63.5 mm diameter, are shown in Fig. 1. At lower solid concentrations, rapid sedimentations occur as soon as the experiments start. On one hand, at higher solid concentrations, the suspensions show initial slow sedimentation and then follow by rapid sedimentation. For the suspensions experiencing slow sedimentation, the period of slow sedimentation increases and the sedimentation rate in the rapid regime decreases, as the solid concentration increases.

Suspensions of further increased solid concentration did not show any sign of rapid sedimentation. In other experiments carried out for different cylinder diameters, we observed similar sedimentation pattern as to the influence of solid concentration on sedimentation phenomena. The effect of cylinder diameter on sedimentation pattern, obtained at 0.4 % volume fraction, is demonstrated in Fig. 2. As shown in this figure, the period of slow settling becomes longer as the diameter decreases. Nevertheless, sedimentation patterns were almost the same irrespective of the diameter. Similar trends were found at different concentrations.

4. DISCUSSION

4.1 Slow Sedimentation Process

Michaels & Bolger⁶⁾ proposed the equation of the sedimentation rate of the boundary between settling sediment and supernatant as a function of the volume fraction of particles on the basis of the experimental result that the density of a settling flocculated suspension is constant. During the sedimentation of a suspension, there exist several forces such as gravity, buoyancy, the network force by floc-

Fig. 1. Height of the sedimentation interface H plotted against elapsed time T obtained for container diameter 63.5 mm.

Fig. 2. Height of the sedimentation interface H plotted against elapsed time T obtained for volume fraction 0.4 %.

floc contact, the drag acting at the interface between the wall of a container and the suspension, and the pressure difference between the top and the bottom of the suspension. On one hand, the sedimentation rate of a suspension can be described by the Darcy law of hydrodynamic permeability, because the sedimentation of the suspension is equivalent to a phenomenon where water flows through the suspension. The pressure difference controlling the flow velocity through the suspension equals the value obtained by subtracting the network force and the wall drag force from the self weight in water. Thus, the settling velocity of the boundary is given by the following equation.¹²⁾

$$U = k[g(\rho_s - \rho_w)\phi - \sigma_y/\Delta Z] - 4k\tau_y \cdot 1/D \quad (1)$$

Where k the hydrodynamic permeability, ρ_s the density of clay particles, ρ_w the density of medium, σ_y the stress due to network formation, τ_y the stress by the drag between suspension and wall, ΔZ the height of suspension with a homogeneous density, D the diameter of sedimentation cylinder. Equation (1) shows that the sedimentation velocity U decreases linearly with the inverse diameter $1/D$ when k , σ_y , τ_y , ΔZ are constants irrespective of the cylinder diameter.

In the slow sedimentation regime, the height of the sediment boundary decreases linearly with time as found from Fig. 2. The figure may mislead readers to think that the rapid sedimentation immediately occurs for $D = 63.5$ mm. This is because the value of x-axis is plotted up to 240 mins. But in fact the slow sedimentation for $D = 63.5$ mm continued for eight minutes. Thus, in the region where the change of the boundary height in 30 seconds was almost constant, a regression line of the height and time was obtained. The slope of the regression line corresponds to the slow settling rate U_s . Obtained values of U_s are plotted against reciprocal diameter $1/D$ for different clay concentrations in Fig. 3. The figure indicates that U_s linearly decreases with increasing $1/D$

when $1/D$ is below 0.06 mm^{-1} . That is, the sedimentation is significantly affected by the wall resistance, once the container diameter exceeds 17 mm. On one hand, when the diameter D is below 13.9 mm, the settling rate is significantly reduced and is constant irrespective of the cylinder diameter. That is, we obtained very interesting results; very slow settling phenomena occur and the drag between the suspension and the wall does not stop settling even in very thin cylinders. From these results, we found that the boundary does not stop but settles with a constant velocity even in thin cylinders, while the settling rate is affected by the diameter of cylinder in the slow settling regime. That is, the wall resistance hinders the settling rate in the early stage of sedimentation and in higher clay concentrations, where the slow settling occurs due to the network formation in the suspension. At this moment, we cannot explain the reason why slow settling and slight seepage occur without stopping sedimentation even in thin cylinders. The existence of flow between the suspension and the wall is probably a candidate to explain the reason. However, we need a further study to unveil this mechanism.

4.2 Settling Rate and Wall Resistance in Rapid Settling Regime

As shown in Fig. 1, in the very dilute suspension, rapid settling happens from the beginning of settling. Increasing the concentration of clay particles brings about the slow settling and then followed by the rapid settling. Looking to settling curves, one can notice that the settling rates in the rapid regime increase with time, slow down after peaks, and then shift to consolidation settling regime. Therefore, to make the change of the rate in the rapid regime visible, the rates at $\phi = 0.4\%$ are plotted against the elapsed time in Fig. 4. These rates were evaluated from the change of the height measured every minute. Figure 4 demonstrates that when the settling process shifts from slow to rapid, the rate sharply rises and

Fig. 3. Relationship between slow constant settling velocity U_s and reciprocal of container diameter $1/D$.

Fig. 4. Settling velocity U plotted against elapsed time T obtained for volume fraction 0.4 %.

then drops down after the peak. Similar trend was observed for different clay concentrations. We calculate an average settling rate from a few values of the rates around the peak by taking into account the scattering of the data and use the calculated value as the settling rate in the rapid regime. The rapid rates are plotted as a function of the diameter of used cylinders in Fig. 5. The figure shows that the rapid rate is constant irrespective of the diameter of cylinder and is thus independent of the diameter. In addition, the rapid settling rate of the boundary between the flocculated suspension and the supernatant is independent of the cylinder diameter at very low volume fraction (below 0.25 %), where the slow settling regime does not appear. Therefore, we found that the wall resistance is negligible in the rapid settling process irrespective of the network formation. Finally, we found that the settling rate in the rapid process is not affected by the wall resistance irrespective of the network formation, indicating that flocs settle with hindering each other.

5. CONCLUSIONS

It has been recognized that the cylinder diameter does not affect the sedimentation phenomena by the study by Michaels & Bolger. While many studies have carried out the experiments on sedimentation after Michael & Bolger, few researchers have investigated the effect of container diameter on the settling behavior of flocculated suspensions. In this context, we have done the precise measurements of the sedimentation velocity of the boundary between sediment and supernatant to examine the effects of the container diameter and the solid concentration for the sedimentation process of the flocculated kaolinite suspensions. That is, we measured the rate of sedimentation by using the three dimensional reading microscope with accuracy of 0.01 mm and examined the effect of the container diameter on the sedimentation rate obtained

Fig. 5. Relationship between maximum settling velocity U_f and reciprocal of container diameter $1/D$.

at various solid volume fractions. Our experimental results demonstrate that the slow sedimentation rates are influenced by the cylinder diameter when the diameter exceeds 21 mm. However, once the cylinder diameter becomes smaller than 14 mm, almost constant rates of very slow sedimentation were observed irrespective of the diameter. This observation implies the following things for the slow settling; 1) the slow sedimentation rate induced by the formation of internal network of flocs is affected by the wall resistance, 2) the wall resistance does not inhibit the sedimentation rates in the thinner cylinders, and 3) upward flow probably exists in the settling sediment.

In contrast, the sedimentation rate in the fast settling regime was constant irrespective of the diameter of the cylinder. From these results, we found the followings for the fast settling: 1) the fast sedimentation rate is independent of the cylinder diameter, 2) the wall resistance is negligible, and thus 3) the rapid sedimentation process is irreverent to the network formation.

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