02 May 2013, 4:00 pm - 6:00 pm

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Commemorate the Legacy of Ralph B. Peck
April 29 - May 4, 2013 CHICAGO
Seventh International Conference on Case Histories in Geotechnical Engineering
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SEDIMENTATION BEHAVIOR OF FLY ASH-KAOLINITE MIXTURES

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ABSTRACT

The sedimentation behavior of fine grained soil is largely dependent on its pore fluid chemistry. Different ionic concentration will lead to different fabrics of soil suspension, such as dispersion, aggregation, and flocculation. The ionic concentration also influences the thickness of the Diffuse Double Layer (DDL), which leads to the change in the final sediment volumes. Besides the ionic concentration influence, adding different amount of fly ash (FA) can also cause different sedimentation behaviors. The objective of this research was to quantify the interaction between fly ash and fine grained soils by comparing the influence of ionic concentration with that of fly ash on the sedimentation behavior of kaolinite. It was found that an increase in the percentage of fly ash in FA-kaolinite mixture could cause an increase in the settling speed. The final sedimentation volume decreased as the ionic concentration increased. The addition of fly ash was found more efficiency than the ionic concentration, because the fly ash could not only interact with kaolinite particles but also increase the ionic concentration in the dissolution by precipitation of Calcium hydroxide and pozzolanic reaction products.

INTRODUCTION

Sediments, deposited in rivers, valleys, and lakes, eventually lead to the formation of soil. Initially, sedimentation occurs when particles settle out from the suspension. As the sediments accumulate, the particles and flocs are brought together and formed soil deposits due to consolidation (Pane & Schiffman 1985). At this stage the material could be defined as a soil, with properties described by traditional parameters (Been & Sills 1981). Studying the process of sedimentation can help engineers understand the stress strain characteristics and hydraulic conductivity of a soil deposit. Understanding the sedimentation behavior of fine grained soil is also very important in many other engineering practices (Imai 1980; Klein 1999; Sridharan and Prakash 2001), such as, developing fly ash grouting (Markou 2002), designing mine tailing dams (Wardwell and Muzzy 1988), purifying containment water, analyzing the drilling mud filtration on borehole stability, studying the interaction between waste leachate and clay liners in landfill (Fam and Dusseault 1998), and determining the geotechnical properties of alluvial soils.

Due to isomorphous substitution, clay particles are usually negatively charged in aqueous environment. A diffuse double layer consisting of abundant positively charged ions neutralizes the negative charges of the clay particles. In a clay-electrolyte system, there are several types of attraction and repulsion forces among clay particles. Double layer repulsion is a force that develops between clay particles. When two particles approach each other, the magnitude of the repulsion force will rely on the interparticle distance and the thickness of the diffuse double layer (Santamarina et al., 2001). Electrostatic attraction is another force that develops between positively charged edges and negatively charged faces of particles. This type of force supports the edge-to-face flocculation fabric of kaolinite system (Van Olphen 1977). Van der Waals force is also an important attractive force in clay colloidal system (Israelachvili 2011). The grain size distribution, solid water concentration, clay mineralogy, and water chemistry were found to greatly influence the sedimentation behavior of fine grained soils (Sridharan and Prakash 1999). The fabric/structure of the slurry and the final sedimentation are largely dependent on these factors. Klein (1999) reported that as ionic concentration increased, the kaolinite fabric varied. In the case of a mixture of kaolinite and a fluid of low ionic concentration, edge-to-face flocculation is favored due to electrostatic attraction (Schofield and Samson 1954). A slight increase in ionic concentration decreases the thickness of the diffuse double layer, and both the edge-to-face attractive force and face-to-face repulsive force decrease. The resulting structure is edge-to-edge flocculated (Van Olphen 1951). At NaCl concentrations greater than 0.1-0.15mol/l, Van der Waals attraction dominates, the face-to-face aggregation occurs

(Palomino and Santamarina 2005). These aggregates link through edge-to-edge and edge-to-face interactions that resulting in a high void ratio net work of kaolinite particles (van Olphen 1977; O'Brien 1971; Rand and Melton 1977). Therefore, a change in ionic strength could lead to a great change in the soil fabric. As a result, the sedimentation behavior will vary significantly. In general, if attractive force is large enough, the particles will collide and combine together which result in a rapid and homogeneous sedimentation process. On the other hand, when the repulsive force is large, each particle will settle at its own speed thus leading to a slow and heterogeneous sedimentation.

Fabric of kaolinite suspension, the sedimentation behavior, influencing factors, and clay mineralogy have been studied extensively by previous researchers (Klein 1999; Sridharan and Prakash 1999; Santamarina et al., 2001; Palomino and Santamarina 2005). The sedimentation behaviors of larger particles such as fly ash and fly ash-clay mixtures, however, were not commonly found in the literature. The fly ash particle size is about 1 to 100 micro-scale, which is 10 to 100 times larger than kaolinite particles. Thus adding fly ash to kaolinite colloidal suspension will very likely lead to different sedimentation volumes and settling speed. This study evaluates the sedimentation behaviors of kaolinite suspensions at different salt concentrations and fly ash-kaolinite mixtures at various ash-to-clay weight ratios. The effects of fly ash on the sedimentation behavior were then quantified by comparing with that of the ionic concentration of the added electrolytes. The preliminary test results may provide some engineering guidance in the application of fly ash on soil modification, ground improvement, and weak soil stabilization.

MATERIALS

Georgia kaolinite (RP-2, Active Minerals International) was used in this research. The kaolinite was an air-float processed clay, with a specific gravity Gs=2.6 and an average aggregates diameter d50=0.004mm.The fly ash used in this study was shipped from Labadie power plants, Missouri. The fly ash was derived from combustion of coal, and collected by using electro-static precipitators. Scanning electron microscopy (SEM) study was carried out on the kaolinite and fly ash particles, the results are presented in Figure 1. The fly ash particles are in round shape. The diameter is ranged from few micros to a hundred micros. Small fly ash particles usually attached to large particles, and the contact area varied significantly. However, kaolinite particles are generally stacked and in platy-shaped. They are randomly scattered, aggregated, and coagulated.

METHODOLOGY

Studies on the sedimentation process have been traditionally undertaken by introducing slurry into a settling cylinder. The position of the solid and clear liquid interface is recorded as a function of time (Pane & Schiffman, 1997). As the particles settled, a well-defined interface was evident between the pool of liquid forming at the top of the column and the kaolinite particles beneath. The vertical movement of this interface from the top of the column was monitored over the duration of the test period.

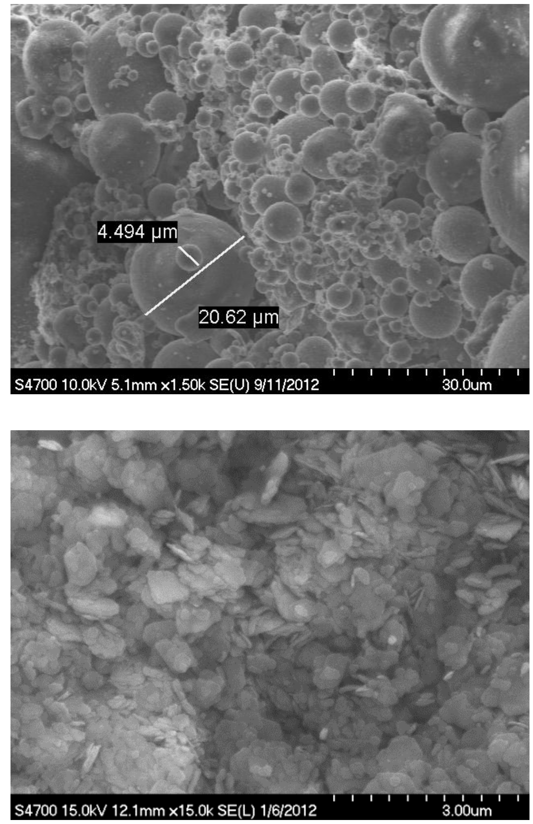

Fig. 1. SEM Image of Fly Ash (top) and Kaolinite Particles (bottom)

In order to study the effect of ionic concentration and fly ash content on the sedimentation behavior of kaolinite suspension, sedimentation tests were carried out on kaolinite, fly ash, and fly ash soil mixtures at different NaCl concentrations. The ionic concentrations were ranged from 1 mol/L, 0.5 mol/L, 0.25 mol/L, 0.13 mol/L, 0.063 mol/L, 0.031 mol/L, 0.003 mol/L, 0.0015 mol/L, 0.00075 mol/L, 0.0004 mol/L, and 0.00002 mol/L, respectively. The test procedures, modified from that of Fam and Dusseault (1998), were used in this study. 1. Collect a total of 10 g of dry kaolinite or fly ash kaolinite mixture. 2. Put the dry soil with 100 ml NaCl solution at different ionic concentrations. 3. Thoroughly mix by shaking the cylinders upside down for 10 times. 4. Then let stand and monitor the sedimentation process with time. 4. Time lapse photos were taken by Digital SLR camera, and sedimentation front (interface) and consolidation volume (bottom part) were read from the stored high resolution images (lens distortion was corrected in Adobe Lightroom 3). 5. Measure the conductivity and pH of the clear fluid and the final sedimentation volume (after test). 6. The results were presented by the sedimentation front and consolidation volume vs. time curves.

RESULTS

Sedimentation behavior of kaolinite is dependent on the suspension density. A series of sedimentation tests on different kaolinite densities were carried out and the results are presented in Figure 2. As the kaolinite density increased, the sedimentation speed increased. The final sediment interface "mud line" (Mpofu et al., 2004) decreased as the kaolinite density increased (Figure 2). In general, pure kaolinite settled very slowly, even if in high densities. Figure 3 shows the sedimentation behavior of kaolinite suspensions at different ionic concentrations. At low concentration (0.00002m/l-0.003m/l), kaolinite suspensions settled in a dispersed form, which was very slowly, and the suspension volume was very large. The final sediment volume (the bottom solid portion) increased with the time increased. As the ionic concentration increased, however, the sedimentation behavior changed distinctly. The suspension settled in a flocculated form. The water solid interface appeared soon after the test started and the sediment volume started decreasing as time increased. This change was attributed to the special fabric that formed under high concentrations where the clay particles are flocculated and aggregated (fabric map, by Palomino and Santamarina 2005). The flocculation and aggregation phenomenon observed in this study agreed well with the results in the literature (Klein 1999, Sridharan and Prakash 1999, 2001; Blewett et al 2001; Angelica et al 2005).

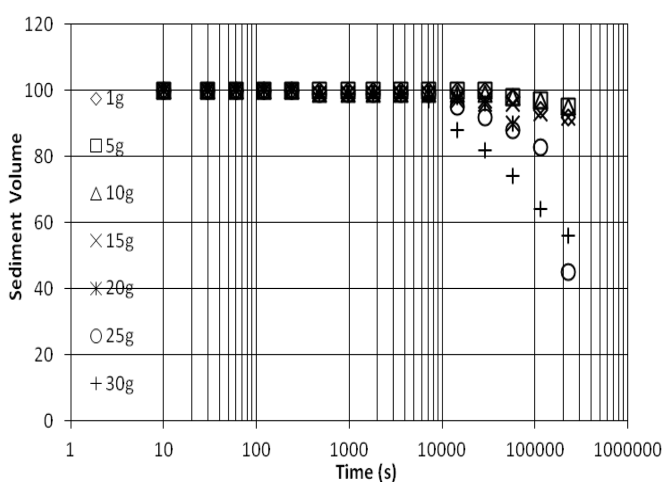

Fig. 2 Sedimentation Behavior of Kaolinite Suspension at Different Densities

Figure 4 displays the sedimentation behavior of fly ash suspensions. Opposed to the phenomenon noticed in kaolinite suspension, the fly ash suspension only had one type of sedimentation behavior, where the sharp interface between accumulated sediment and clear fluid decreased gradually with time increased. Although the NaCl concentration varied from 1 mol/L to 0.00002 mol/L, the ionic concentrations were found almost had no influence on the sedimentation behavior of fly ash particles, because all the curves are mixed and overlapped with each other. The settlements of all the fly ash samples were stopped at the same time, approximately at 1000s.

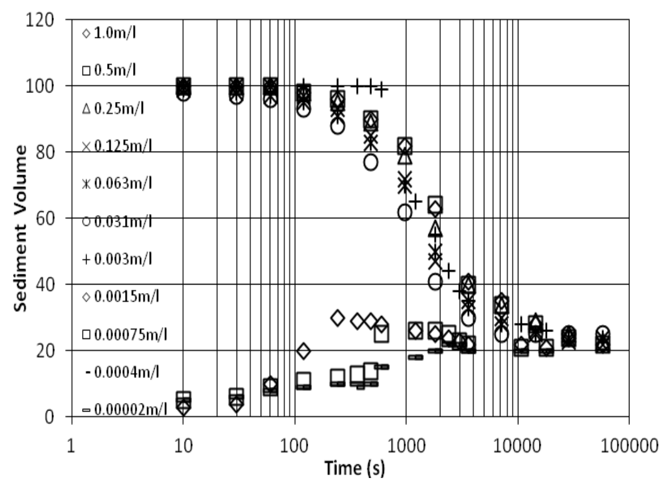

Fig. 3 Sedimentation Behavior of Kaolinite suspension at Different Ionic Concentrations

Different amount of FA was added to kaolinite suspensions, the weight ratio varied from 1% to 50%, their sedimentation behaviors were presented Figure 5. A very clear trend was observed that as fly ash ratios increased, the fly ash soil mixture settled more and more fast. The water solid interface appeared very early and the sedimentation speed increased as the fly ash content increased. The increase of the sedimentation speed was more dramatic when Fly ash content was greater than 5%, where the sedimentation ceasing time decreased to approximately 1000s.

Figures 6 to 10 displayed the sedimentation behaviors of fly ash kaolinite mixtures at various ionic concentrations and various fly ash contents. At low fly ash content (Figure 6), the sedimentation behavior seems more governed by the ionic concentration, as the ionic concentration increased, the mixture's settling speed increased and the sedimentation ceased at an earlier time. At about 10% concentration, however, the influence of the ionic concentration largely decreased, where low concentration suspensions showed a slow settling speed, but the difference between high ionic concentrations was very small. Figures 8 to 10 show the sedimentation behavior of the mixtures at high fly ash content. The ionic concentration was found has no effects on the sedimentation behavior since all the sedimentation curves are the same and overlapped with each other. No matter how high or how low the ionic concentration was, the curves were all mixed and overlapped with each other.

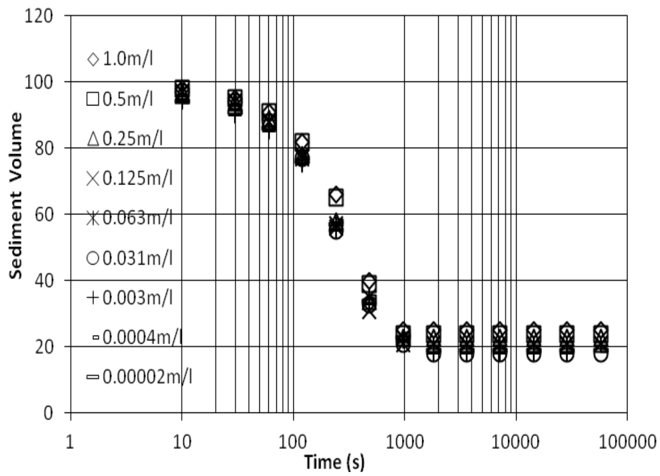

Fig. 4 Fly Ash Sedimentation Behaviors at Different Ionic Concentrations

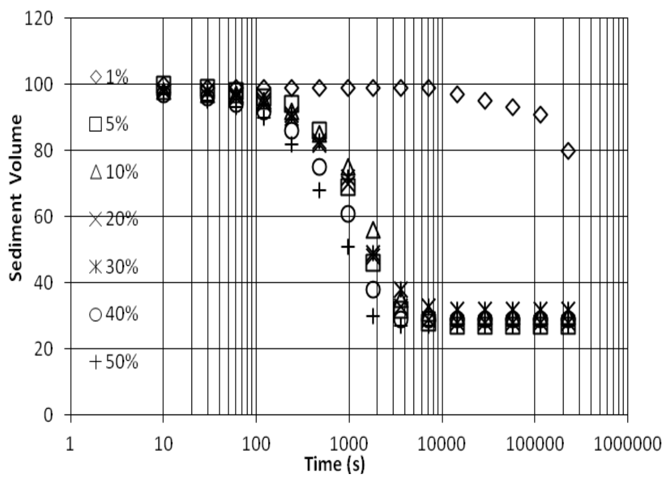

Fig. 5 Kaolinite fly Ash Mixture Sedimentation Behaviors at Different Ash to Kaolinite Weight Ratios

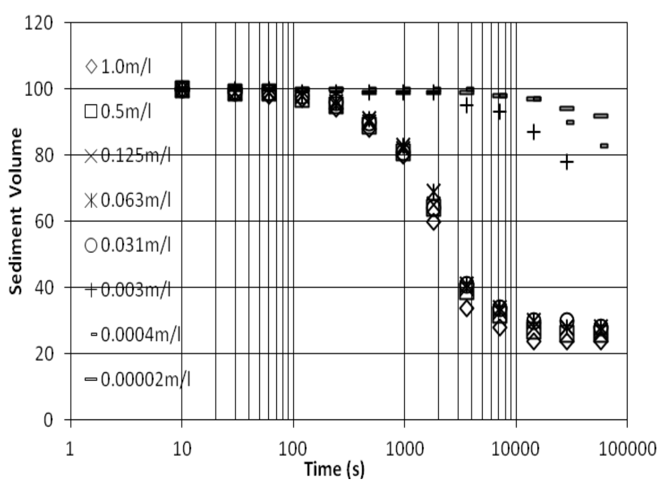

Fig. 6 Kaolinite Fly Ash Sedimentation Behaviors(99%Kaolinite+1%FA)

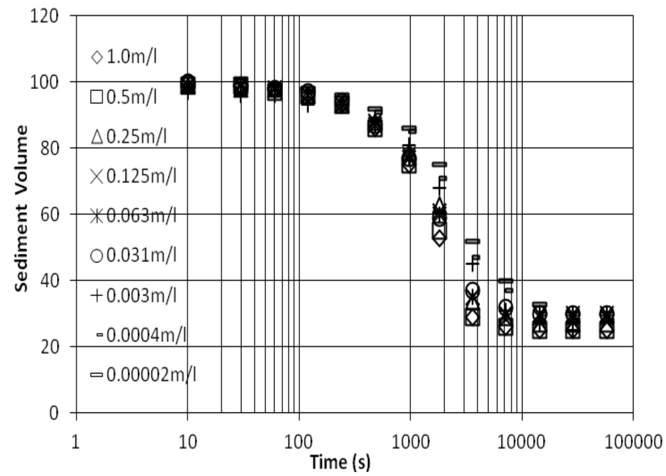

Fig. 7 Kaolinite Fly ash Sedimentation Behaviors (90%Kaolinite+10%FA)

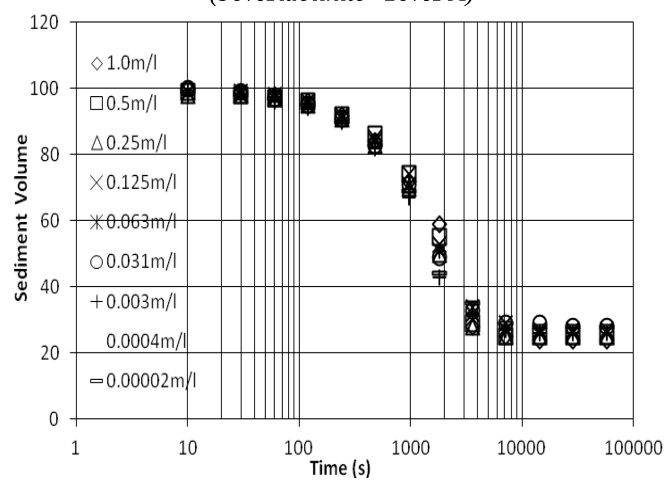

Fig. 8 Kaolinite Fly Ash Sedimentation Behaviors (80%Kaolinite+20%FA)

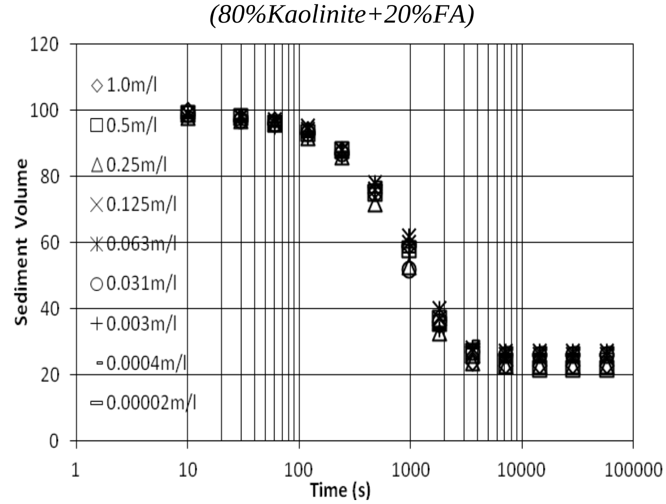

Fig. 9 Kaolinite Fly Ash Sedimentation Behaviors (60%Kaolinite+40%FA)

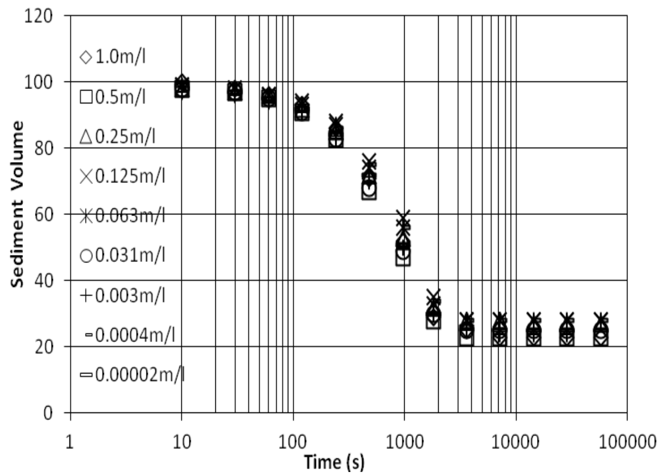

Fig. 10 Kaolinite Fly Ash Sedimentation Behaviors (50%Kaolinite+50%FA)

DISCUSSIONS

A study on the effect of density on the sedimentation behavior of kaolinite was carried out (Figure 2). Within the duration of the test period, an increase of the solid liquid concentration causes the kaolinite particles to settle at a faster rate (Blewett et al. 2001). This is explained by the production of a more aggregated flocculated structure with increasing mixing-liquid concentration (Sridharan & Prakash, 1999). At low density, the kaolinite particles are dispersed and no interactions happen between kaolinite particles. At high density, however, particles colliding and interacting with each other so that to form a flocculated fabric. Because the larger flocs settling faster than dispersed particles, the high density kaolinite suspension thus settled faster than the low density suspension. A final sediment volume versus ionic concentration of kaolinite, fly ash and fly ash kaolinite mixtures were presented in Figure 11. The kaolinite and fly ash had evident difference, the final sedimentation volume of kaolinite increased as the ionic concentration decreased, however, the final sedimentation volume of fly ash decreased as the ionic concentration increased. Klein (1999) explained the relationship between final sedimentation volume and ionic concentration. The increase in the concentration of a solution can cause the diffuse double layer to shrink, thus the repulsion force between two clay particles would decrease and the attraction force would increase. On macro scale, this decrease of the thickness of the diffuse double layer may explain why the final sedimentation volumes vary with the ionic concentrations. The larger the final sedimentation volume, the thicker the diffuse double layer of the clay particles.

The sedimentation behavior of fly ash kaolinite mixtures were of more interesting. At low ionic concentrations (0.00002m/l - 0.003m/l) and low fly ash content (less than 5%), the suspension was settled in a dispersed fabric, where the sharp interface between the suspension and clear fluid was not evident and the sedimentation volume increased as the suspension part became thinner and clearer. At high FA weight ratio (larger than 5%), the influence of the ionic concentration became less important. It was observed that at low fly ash weight ratio, high NaCl concentration accelerated the settling speed (Figures 6 and 7). However, at high fly ash weight ratio, the rate of settlement of the fly ash-kaolinite mixtures did not change with NaCl concentrations (Figure 8 to Figure 10). The high fly ash content kaolinite-fly ash mixtures showed two distinct layers, the supernatant and the sediment, which indicated a flocculated structure (Kaya et al., 2003). The sharp interface between the sediment solid and clear fluid appeared shortly after the test started, and the sediment volume decreased as the time increased. Since fly ash would hydrate when mixed with water due to the hydration of chemical content, such as calcium oxide (CaO), silicon dioxide (SiO2) and other materials, hence the ionic concentration of the solution increased. The increase of the ionic concentration might cause clay particles to flocculate thus result in a flocculated fabric. It is also hypothesized that fly ash particles would collide with the kaolinite particles and form agglomerates of FA and kaolinite during the sedimentation process.

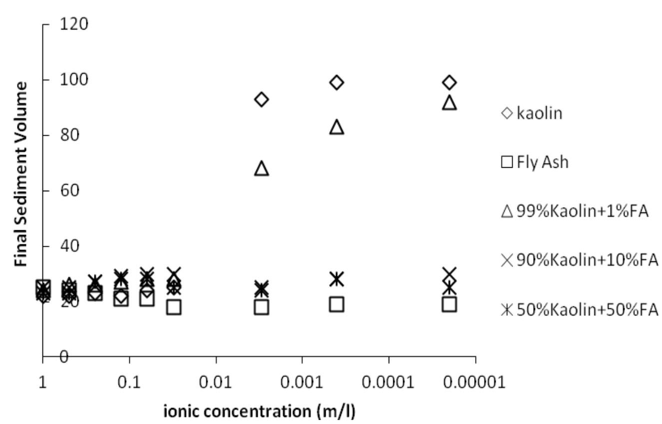

Fig. 11 Final Volumes versus Ionic Concentration of Kaolinite, Fly Ash, and Fly Ash Kaolinite Mixtures

By measuring the conductivity of the fly ash and fly ash kaolinite mixtures, it is found that the fly ash can result in the electrical conductivity to increase, which might due to the hydration of the fly ash particles and releasing of some heavy metal ions. However, the conductivity change was not in proportion with the addition of the fly ash content. As shown in Figure 12, once the conductivity increased to about 4.0 ms/cm, it became constant, no matter how high the fly ash content increased. The increase of the electrical conductivity could effectively explain why the fly ash kaolinite mixture settled in a flocculated fabric. The addition of fly ash can cause the ionic concentration increase, thus result in the kaolinite particles to flocculate and aggregate. After mixing, shaking and agitating, fly ash particles would evenly disperse into the flocculated kaolinite structures. During settling, fly ash particles settled faster which would collide and press with the flocculated kaolinite aggregates, therefore the settling speed of the suspension increased. Compared with the sedimentation behavior of pure kaolinite, the addition of fly ash largely increased the sedimentation speed. If more fly ash is added, the collision and interaction between fly ash particles and kaolinite aggregates would be more pronounced, thus causing the mixture to settle even faster.

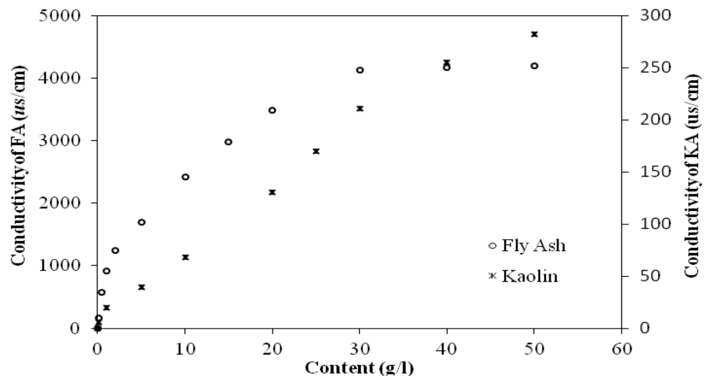

Fig. 12 Conductivity of Fly ash and Kaolin at Different Densities (Kaolin plotted on secondary y-axis)

SUMMARY

A brief literature review was carried out on the sedimentation behavior of kaolinite. The sedimentation behavior of kaolinite, fly ash, and fly ash kaolinite mixtures were studied. The ionic concentrations were found to result in different interactions between kaolinite particles and cause the settlement behavior changes. Changing the ionic concentration can also influence the thickness of the Diffuse Double Layer (DDL), which may also affect the final sediment volume. Besides the ionic concentration influence, the addition of fly ash was found more evident in changing the sedimentation behavior of kaolinite suspensions. The ionic concentration, however, had small influence on the fly ash sedimentation process. Compared with the mixing of fly ash particles, the NaCl concentration was found to have less influence on the kaolinite suspensions. The ionic concentration had more effects when the fly ash concentration was low; however, when the fly ash content was high, the sedimentation behavior was more governed by the fly ash particles than the ionic concentration. Finally, an increase in the percentage of fly ash could cause an increase of the settling speed of fly ash kaolinite soil mixtures.

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