# 1-D Consolidation characteristics of kaolinitebentonite mixtures with different pore fluid salinity



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## ABSTRACT

This study investigates the 1-D consolidation characteristics of kaolinite-bentonite mixtures with the variation of different chemical and physical properties. A laboratory technique has been developed for the preparation of samples for this study. The samples were prepared at a moisture content level of 2% above the respective liquid limit of each clay sample mixture. The correlation of the measured coefficient of consolidation ( $C_V$ ) and the compression index ( $C_c$ ) of the clay mixtures with the key influencing factors such as salinity level of pore fluid (pore fluid chemistry), mineral composition, liquid limit, plastic limit and surface area of clay minerals were analyzed in detail. The surface area of kaolinite and the expansive clay (bentonite) was measured using the methylene blue analysis.

## RÉSUMÉ

Cette étude comprend la consolidation unidimensionnelle d'un mélange de kaolinite-bentonite en fonction de ses propriétés chimiques et physiques. On a développé une technique d'échantillonnage en laboratoire pour cette étude. Les échantillons ont été préparés à une teneur en eau de 2% au-dessus de la limite de liquidité de chaque mélange d'argile. L'analyse des résultats de consolidation démontre une corrélation du coefficient de consolidation ( $C_v$ ) et l'indice de compression (Cc) des mélanges d'argile avec la salinité de l'eau dans les pores, la composition minérale, la limite de liquidité, la limite plastique de l'argile, et la superficie des minéraux d'argile. Les surfaces spécifiques de la kaolinite et de l'argile gonflante (bentonite) ont été mesurées à partir de l'essai au bleu de méthylène.

## 1 INTRODUCTION

Consolidation characteristics of clay mixture are mainly influenced by the pore fluid salinity and the clay mineral matrix (mineral composition). Diffused double layer in clays control the impact of pore fluid salinity on the consolidation characteristics. Most clay minerals have a negative charge on the surface and when the pore fluid has exchangeable cations it forms a stern layer on the surface. When the clay sample is exposed to saline pore fluid, the inward salt diffusion occurs at the clay surface. This neutralization process reduces the repulsive forces between the clay layers; thus consolidation rate highly depends on the clay mineral composition and the salinity level of the pore fluid.

Di Maio et al. (2004) have studied the volume change behaviour of clays and shown that pore fluid has a significant influence on the compressibility and swelling properties of clays. Robinson and Allam (1998) studied the effects of clay mineralogy on the coefficient of consolidation. Their results revealed that the consolidation characteristics are influenced by both mineralogy and pore fluid salinity. This outcome encourages the research investigation on the consolidation characteristics of clay mixtures. Kennv (1967) has found that mineral mixtures have some unique properties compared to their individual minerals and he has suggested that there have been inadequate studies conducted on the kaolin family of minerals.

The results from the above literatures are hardly comparable because, the researchers have followed

different methodology and mainly focused on a specific factor of influence. This study has been conducted to understand the impact of mineral composition and pore fluid salinity on the consolidation characteristics and the influence of liquid limit, plasticity index, and surface area on the 1-D consolidation behaviours.

## 2 LIQUID LIMIT AND PLASTICITY INDEX

Commercial kaolinite and bentonite were used in this study. The kaolinite sample has an average particle size of 2  $\mu$ m and a specific gravity value of 2.59, where as the average particle size and the specific gravity of bentonite sample was 2 nm and 2.45, respectively. Fall cone method was used to determine the liquid limit (LL) of the clay mixtures. The tests were conducted for different clay mixtures by varying the bentonite content and these clay mixtures were tested with different pore fluid concentrations.

Figure 1 shows the LL values of different clay mixtures with pore fluid salinity variations. The results revealed two important LL variation patterns. All the clay mixtures showed a decrease in LL with the increase of pore fluid salinity and an increase in LL with increase of bentonite content in the clay mixture. The 1-D consolidation test was conducted on the clay mixtures by moulding the sample according to the LL of each clay mixture; therefore LL has some influence on the consolidation characteristics of clay mixtures.



Figure 1. Liquid limit versus pore fluid salinity curves for different clay mixtures.



Figure 2. Plasticity index versus pore fluid salinity curves for different clay mixtures.

Plasticity index (PI) of different clay mixtures in percentage with varying pore fluid salinity is shown in Figure 2. The results showed the same pattern as the LL variation and this lead to the following conclusions. Higher the bentonite contents in a clay mixture higher the value of LL and PI. Higher pore fluid salinity yields a lower LL and PI value.

## 3 CONSOLIDATION CHARACTERISTICS

Consolidation characteristics of clay mixtures were studied by conducting the standard 1-D consolidation test. Clay mixtures were prepared by mixing kaolinite and bentonite minerals in different proportions with varying pore fluid salinity levels (0% - 10% NaCl concentration). The clay mixtures were remoulded at a moisture content level of 2% above the respective LL of each clay mixture. A fixed ring oedometer test was conducted on the remoulded clay samples of 60 mm diameter and 20 mm thickness. A load increment ratio (ratio between the increment in the normal stress and the existing normal stress) of 1.0 was adopted throughout the consolidation test and the load was applied for a sufficient time to complete the primary consolidation. The clay mixtures underwent five load increments in the consolidation test and each load increment lasted for 24 hours. Initial and final (after five days consolidation) moisture contents of each sample were measured to determine the void ratio variation of the clay mixtures.

#### 3.1 Coefficient of Consolidation (C<sub>V</sub>)

The coefficient of consolidation ( $C_V$ ) is a key parameter in the consolidation analysis.  $C_V$  gives the rate at which the pore pressure dissipation occurs in soils when the soil is subjected to a normal stress. Clay mixtures generally have a lower value of  $C_V$  compared to soils because of the lower permeability and higher compressibility nature in clays.

Several methods have been established to calculate the  $C_V$  value of clay mixtures. Taylor (1948) developed the square root of time fitting method to calculate  $C_V$  of a consolidation test and this method is used in geotechnical engineering analysis mainly because it allows to place the next load increment as soon as it reaches the  $t_{90}$  (square root of time for 90% consolidation) value.



Figure 3. Coefficient of consolidation versus normal stress curves for clay mixtures (75% kaolinite and 25% bentonite) with pore fluids of different salinity levels.

Figure 3 shows the  $C_V$  variation of a clay mixture having 75% kaolinite and 25% bentonite by dry weight, mixed with different pore fluids. Pore fluids with four different salinity levels were used in this study to understand the impact of pore fluid salinity on the  $C_V$ behaviour of the clay mixtures. The result shows that higher  $C_V$  values were observed at higher pore fluid salinity levels and the  $C_V$  value of this clay mixture with distilled water reported a small value of 0.01 mm<sup>2</sup>/sec at high normal stresses (400 – 575 kPa). Small  $C_V$  values can cause prolonged consolidation in the construction stages. Several other clay mixtures with different bentonite proportions were tested with different pore fluid salinities and the results revealed important behaviours. All five clay mixtures showed high  $C_V$  values for the high salinity pore fluids but the impact of pore fluid salinity on  $C_V$  variation diminished with the increasing bentonite content in the clay mixture. The pure bentonite mixture with four different pore fluids showed a  $C_V$  variation range of 0.01 mm<sup>2</sup>/sec to 0.02 mm<sup>2</sup>/sec. In contrast, the pure kaolinite mixture showed a  $C_V$  variation range of 0.55 mm<sup>2</sup>/sec to 1.08 mm<sup>2</sup>/sec with the same pore fluids. This analysis reveals that the pore fluid salinity has a significant influence on the  $C_V$  variation of kaolinite enriched clay mixtures but the influence of pore fluid salinity on the  $C_V$  of the bentonite enriched clay mixtures are minimal.

Figure 4 shows the C<sub>V</sub> variation of different clay mixtures with 2% NaCl pore fluid. Five clay mixtures with different bentonite proportions were tested to study the impact of mineral composition on the C<sub>V</sub> behaviour. The result shows that the bentonite content in the clay mixture has a significant influence on the C<sub>V</sub> variation. The clay mixture having pure kaolinite showed a high C<sub>V</sub> value of 0.82 mm<sup>2</sup>/sec compared to the other clay mixtures having bentonite in the mixture. The clay mixture having 25% of bentonite in the sample showed an immense difference on the C<sub>V</sub> behaviour compared to the clay mixture having no bentonite (i.e. pure kaolinite), but the Cy behaviour of the clay mixtures having 25% to 75% bentonite and pure bentonite were very similar. The five mixtures were tested with pore fluids of four different salinity levels and the results showed some key behaviour. In all experiments the C<sub>V</sub> value decreased with increasing bentonite content in the clay mixtures. Pure kaolinite samples showed an increase in the C<sub>V</sub> value with the increase of pore fluid salinity and the influence of mineral composition on the Cy behaviour was significant in pore fluids with high salinities. This analysis reveals that up to a certain level, bentonite content in a clay mixture has an influence on the C<sub>v</sub> value.

Das (2002) has predicted that  $C_V$  has an inverse relationship with LL, i.e.  $C_V$  generally increases as the LL of soil decreases. The initial LL analysis shows that for a particular clay mixture, LL decreases with increase of pore fluid salinity level. Figure 3 shows that  $C_V$  value increases with the increase of pore fluid salinity level. Similarly LL analysis shows that at a particular pore fluid salinity level the LL value increases with the bentonite content of a clay mixture. Figure 4 show that  $C_V$  value decreases with bentonite content of a clay mixture. This study affirms the predicted relationship between the  $C_V$  variation and the LL in a clay mixture.

#### 3.2 Void ratio (e)

Void ratio is an important consolidation characteristic and explains the compressibility of the clay mixtures. Clay mixtures were prepared with different proportions of kaolinite and bentonite with different pore fluids to understand the impact of both mineral composition and pore fluid salinity on the void ratio.



Figure 4. Coefficient of consolidation versus normal stress curves for different clay mixtures with 2% NaCl pore fluid.



Figure 5. Void ratio versus normal stress curves of clay mixtures (25% kaolinite and 75% bentonite) with different salinity levels of pore fluids.

The void ratio variation of a clay mixture having 25% kaolinite and 75% bentonite with different pore fluids was shown in Figure 5. The result showed that the pore fluid salinity has a significant influence on the void ratio variation of this clay mixture. Several other clay mixtures were tested with different pore fluids and the void ratio behaviour pattern were similar to Figure 5. All the results revealed that initial and final void ratios decrease with the increase of pore fluid salinity level, but the impact of the pore fluid salinity after a level of 5% NaCl concentration is minimal. Mitchell (1993) stated that the compression behaviour in nonexpansive clay minerals has a lesser influence by the pore water chemistry compared to the expansive clay minerals. In pure kaolinite the void ratio variation with different pore fluids lies in a range of 0.47 to 1.25, but in bentonite this range is 0.83 to 4.86. This result confirms the impact of pore fluid salinity on the expansive clay minerals. This analysis showed that the void ratio variation range increased with the increase of bentonite content in the clay mixture.

Figure 6 shows the void ratio versus normal stress variation for different clay mixtures with distilled water as the pore fluid. The results revealed that the bentonite content has an influence on the void ratio variation in a clay mixture. These five clay mixtures were tested with four different pore fluids having different salinity levels, and the results showed that void ratio variation range in clay mixture decreases with the increase of salinity level in the pore fluid. Compared to kaolinite, bentonite clay showed a significant reduction in the void ratio variation with the increase of pore fluid salinity level.



Figure 6. Void ratio versus normal stress curves for different clay mixtures with distilled water as the pore fluid.

#### 3.3 Compression Index (C<sub>c</sub>)

Compression index ( $C_c$ ) is regarded as the measure of the compressibility in clays. Compression index is the negative gradient of a semi logarithmic void ratio vs. log P (normal stress) plot.

 $C_c$  variation of five clay mixtures with different pore fluid salinity levels is shown in Figure 7. Pure bentonite sample is significantly influenced by the salinity level of the pore fluid, especially the salinity variation from distilled water to 2% NaCl concentration. The impact of pore fluid salinity on the clay mixtures is minimal after 5% NaCl concentration. The results show that 25% inclusion of bentonite clay in to the clay mixture yields a considerable increase in  $C_c$  compared to the pure kaolinite clay sample. The result in Figure 7 shows that a high bentonite content in a clay mixture and at a low salinity level of pore fluid yields a high value for  $C_c$ .

## 4 SPECIFIC SURFACE AREA (S<sub>S</sub>)

The specific surface area ( $S_S$ ) of clay minerals is defined as the ratio between surface area and mass of the clay minerals. Few techniques such as methylene blue analysis (absorption technique), gas adsorption technique and electron microscopy are used to measure the  $S_S$  of clay minerals. Among these methods, gas adsorption technique is conducted under dry conditions; thus, to measure the surface area of expansive clays such as bentonite this method is not appropriate. Compared to electron microscopy the methylene blue analysis is simple and can be easily implemented in laboratories. Methyelene blue analysis also facilitates the surface area measurement of expansive clays because the test is conducted in water suspensions and enables expansive clays to expose the maximum possible surface area. Farrar and Coleman (1967) have proposed a technique to estimate the S<sub>S</sub> using the LL of clays. This technique was proposed based on their study of nineteen British clays having LL range between 28 and 121. Bentonite enriched clay mixtures generally have a higher value of LL; thus, methyelene blue analysis is considered as the suitable method to study the S<sub>S</sub> of clay mixtures.



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Figure 7. Compression index versus pore fluid salinity curves for different clay mixtures.

Santamarina et al. (2002) have proposed a methyelene blue spot test technique to analyse the specific surface area of both expansive and non expansive clay minerals. This technique was adopted to test the surface area variation of clay mixtures with mineral composition and pore fluid salinity variation. The result shows that both mineral composition and salinity level of pore fluid has an influence on the  $S_S$  of clay mixtures. Since the  $S_S$  affects the inter particle forces in clay mixtures,  $S_S$  have an influence on the 1-D consolidation behaviour of clay mixtures.

 $S_{\rm S}$  variation of clay mixtures with distilled water as the pore fluid is shown in Figure 8. The results revealed that the bentonite content in a clay mixture has a significant influence on the  $S_{\rm S}$  value. To investigate the influence of pore fluid salinity on the  $S_{\rm S}$  pure kaolinite and bentonite samples were tested with four pore fluids having different salinity levels. Figure 9 shows the variation of  $S_{\rm S}$  with different pore fluids for the two samples. The influence of the pore fluid salinity on the kaolinite samples is very minimal compared to the bentonite samples. Compared to kaolinite samples, bentonite samples showed a significant decrease in the  $S_{\rm S}$  with the increasing salinity level of pore fluids.



Figure 8. Specific surface area versus bentonite content curve for different clay mixtures with distilled water as the pore fluid.



Figure 9. Specific surface area versus pore fluid salinity curve for kaolinite and bentonite.

#### 5 CONCLUSION

This paper describes an experimental investigation to study the impact of mineral composition and pore fluid salinity on the 1-D consolidation characteristics. The results show that the consolidation characteristics of bentonite enriched clay mixtures are severely influenced by pore fluid salinity compared to the kaolinite enriched clay mixtures. A small amount of bentonite content in a clay mixture has a significant impact on the consolidation characteristics. At lower level of bentonite content and higher level of pore fluid salinity the clay mixtures showed a higher value for rate of consolidation and a lower value for the total consolidation. Since most clay shales have kaolinite and bentonite as their main mineral compositions, this study provides a good understanding of the consolidation characteristics of clay shale.

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