Influence of Mineral Constituents on One-dimensional Compression Behaviour of Clayey Soils

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ABSTRACT: Only few data are available concerning the effect of the four main clay minerals, kaolinite (K), illite (I), montmorillonite (M) and chlorite (C), on the mechanical properties of clayey soils. This paper discusses the effect of different mineral contents on the compression and swelling indexes of clay mixtures in order to provide correlations between the mineralogical content of a clayey soil and its compressive properties. Four pure clay powders were used to prepare 34 clay mixtures (different proportions of K+I, K+I+M, K+I+C). Conventional oedometer tests were conducted on all the prepared samples. Based on the test results, the evolution of the compressive properties with the proportions of pure clays was estimated and relevant correlations are suggested. All the results demonstrate that the compression and swelling indexes are reasonably well correlated to the proportion of clay minerals. The content in montmorillonite influences significantly the compressive properties of clayey soils, and the contents of illite and chlorite are less influential when added to kaolinite based clayey soils. Moreover, 15 samples with different proportions of K+I+M+C were prepared and tested, and the proposed correlations were validated in light of the results obtained on these materials.

KEYWORDS: Kaolinite, Illite, Montmorillonite, Chlorite, Compression index, Swelling index.

1. INTRODUCTION

In coastal areas, clay deposits are very common, and analyses have showed that the main mineral constituents are kaolinite, illite, montmorillonite and chlorite (Xu et al. 2009; Ma et al. 2010, Zeng et al. 2011). Mineralogy is the primary factor controlling the size, shape, and properties of soil particles (Mitchell and Soga 2005). These same factors determine the possible ranges of chemical, physical and mechanical properties of any given soil (characterization of the strength (Tiwari and Ajmera 2011a; Tiwari and Ajmera 2011b; Mesri and Olson 1971), index properties (Yin 2001; Schmitz et al. 2004; Polidori 2007), permeability (Horpibulsuk et al. 2011; Yamada et al. 2011)). The constitutive modeling of natural clay behavior in various locations in the world (St Herblain clay in France (Yin et al. 2010; Yin and Hicher, 2008), Gulf of Guinea clay in (Yin et al. 2011a), Wenzhou clay in China (Wang and Yin 2012), Finnish clays (Yin et al. 2011b, c; Karstunen and Yin 2010; Yin et al. 2009; Yu et al. 2013; Yin et al. 2012)) also indicate the important influence of the type and content of clay minerals on the mechanical characteristics of soils.

The compressibility of soils is an important factor in the design of foundations and embankment structures. For instance, Kumar and Wood (1999) analyzed the compressive behavior of a mixture of kaolinite and silt. Yin (2000), using the content of clay, silt and sand gave an expression of the compression index through an intermediate variable plastic index. During the last decades, extensive studies have been reported in the literature about the role of the mineral composition on the compressive properties of clayey soils (Mesri and Olson 1971; Di Maio 2004). However, little research has been done on the content of chlorite clay, and so far even less on the influence of these four main clay minerals on the compressive properties of clayey soils.

For this purpose, we decided to study the mechanical properties of reconstituted soil specimens prepared by mixing 49 different proportions of commercially available powdered pure mineralogical clays: kaolinite, illite, montmorillonite and chlorite.

Firstly, three series of conventional oedometer tests were conducted on 34 samples (K+I, K+I+M, K+I+C) to measure their compressive properties, i.e. compression and swelling indexes. Correlations between the compression and swelling indexes and the content of individual pure clay minerals have been suggested by non-linear interpolation functions. Finally, the suggested relationships were verified by using the additional results obtained on 15 specimens prepared by mixing the four pure clay powders (K+I+M+C).

2. MATERIALS AND METHODS

2.1 Clay Minerals

Different proportions of commercially available calcium montmorillonite (hereinafter referred to as montmorillonite), kaolinite, illite and chlorite were mixed in the laboratory to compose 49 different soil specimens. These four different clay mineral powders were all obtained from a commercial company. X-ray diffraction (XRD) tests (Figure 1(a)) and laser particle size analysis (Figure 1(b)) were carried out on these pure clays, and the liquid and plastic limits were measured according to the ASTM procedures. Specific gravities were obtained by the pycnometer. XRD diagrams were obtained using an X-ray diffractometer with Cu-kα radiation and Ni filter, at a voltage of 40 kV and a current of 40 mA. Physical properties of the four pure clays are summarized in Table 1.

We have to point out that it is difficult to find absolutely pure clays with the same particle size distribution, especially for illite, as indicated in several references (Tiwari and Ajmera 2011a; Tiwari and Ajmera 2011b; Schmitz et al. 2004; Horpibulsuk et al. 2011). Because this study is focused on the trend of each clay mineral influence, all the selected materials are appropriate. Moreover, in agreement with already published studies, it can be assumed that each of the selected materials represent the physical properties of its clay mineral constituent.

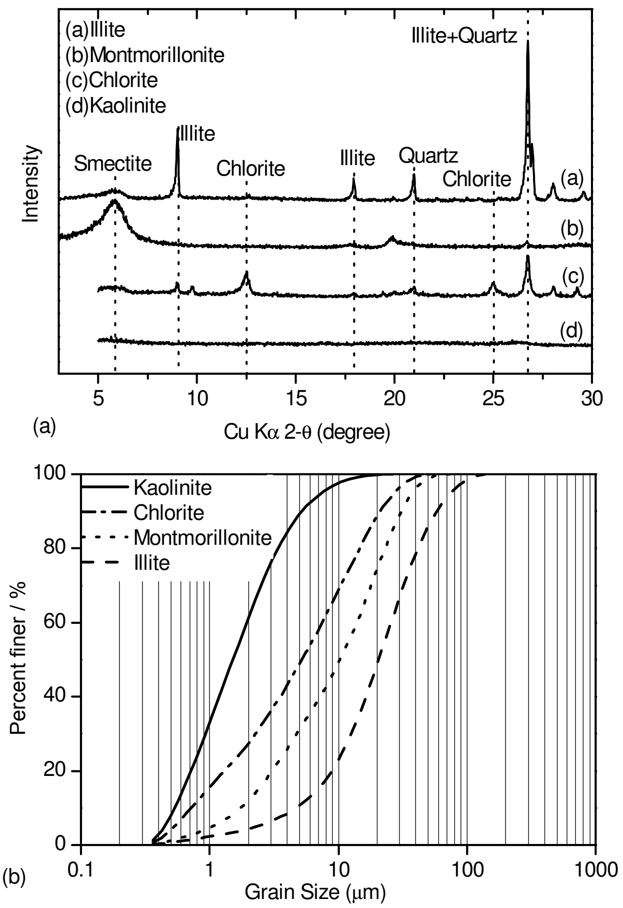


Figure 1 Properties of selected clay powders: (a) XRD tests; (b) Grain size distributions.

Table 1 Basic properties of the tested powders of pure clays

Properties	Kaolinite	Illite	Montmorillonite	Chlorite
Specific gravity, G_s	2.66	2.72	2.69	2.64
Liquid limit, LL (%)	76.3	47.1	121.9	40.3
Plastic limit, PL (%)	60.3	27.9	66.6	25.2
Plasticity index, PI (%)	16	19.2	55.3	15.1
Compression index, C_c	0.17	0.25	0.92	0.25
Swelling index, C_s	0.025	0.041	0.101	0.035

2.2 Methodology

2.2.1 Test Program

49 specimens with different proportions of pure clays were prepared: 4 were mixtures of kaolinite and illite (Table 2a); 15 were mixtures of kaolinite, illite and montmorillonite (Table 2b); 15 were mixtures of kaolinite, illite and chlorite (Table 2c); and the remaining 15 were mixtures of the four pure clays (Table 2d). Each specimen was prepared from a slurry by mixing dry powders and distilled water with an initial water content equal to 1.8 times the liquid limit. The first three series were used for determining correlations between the compression and swelling indexes and the proportions of clay minerals and the last series was used to validate these correlations.

2.2.2 Conventional Oedometer Tests

All laboratory tests were conducted in standard fixed ring oedometers with brass rings of 30 cm^2 in area (diameter d = 61.8 mm) and 20 mm in thickness. The interior of the ring was lubricated with silicon grease to minimize the side friction between the ring and the specimen. All specimens were saturated under a vertical stress of 25 kPa for more than 7 days. Then, conventional oedometer tests were carried out according to the ASTM standard. Each specimen was subjected to successive vertical stresses equal to 25 kPa, 50 kPa, 100 kPa, 200 kPa, 100 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa, and 1600 kPa corresponding to stages of loading, unloading and reloading. The duration of each stress step was 24 hours. Then, the compression curves were obtained, from which the compression and swelling indexes for each specimen were measured.

Table 2 Clay mixtures with different proportions of pure clays

(a) mixtures of kaolinite and illite (1x4=4 samples)

	Case 1	Case 2	Case 3	Case 4
K	20%	40%	60%	80%
I	80%	60%	40%	20%

(b) mixtures of kaolinite, illite, montmorillonite (3x5=15 samples)

	Case 1	Case 2	Case3	Case4	Case5
K+I [K/(K+I): 20%, 40%, 80%]	90%	70%	50%	30%	10%
M	10%	30%	50%	70%	90%

(c) mixtures of kaolinite, illite, chlorite (3x5=15 samples)

	Case 1	Case 2	Case3	Case4	Case5
K+I [K/(K+I): 20%, 40%, 80%]	90%	70%	50%	30%	10%
C	10%	30%	50%	70%	90%

(d) mixtures of kaolinite, illite, montmorillonite, chlorite (3x5=15 samples)

	Case 1	Case 2	Case3	Case4	Case5
K+I [K/(K+I)=40%]	90%	70%	50%	30%	10%
C+M [C/(C+M): 20%, 40%, 80%]	10%	30%	50%	70%	90%

* K-Kaolinite, I-Illite, M-Montmorillonite, C-Chlorite

3. TEST RESULTS

3.1 Compressive Properties of Four Pure Clays

Results of the oedometer tests performed on specimens of pure clays are shown in Figure 2 in the form of traditional plots giving the void ratio versus the logarithm of the effective vertical stress e-log(σ'). Because all the specimens were reconstituted clay mixtures consolidated under σ'=25 kPa, the preconsolidation pressure cannot be displayed in the loading portions of the e-log(σ') curves shown in Figure 2. From these curves, the compression index (C_c=$\Delta e/\Delta \log\sigma'$ based on loading curves with σ'=200 to 1600 kPa) and the swelling index (C_s=$\Delta e/\Delta \log\sigma'$ based on unloading-reloading loops with σ'=25 to 200 kPa) could be obtained for each pure clay. The measured values of the compression and swelling indexes of the four pure clays are listed in Table 1. We can observe that the compression and swelling indexes of the montmorillonite clay are significantly higher than the ones obtained on the other clays, in agreement with high values of the Atterberg's limits. Illite and chlorite clays have similar values for these two indexes, whereas the kaolinite clay has slightly smaller values of these two indexes.

With the same method, the *e*-log(σ') curves and the compression and swelling indexes could be obtained for all clay mixtures, as presented in the following sections.

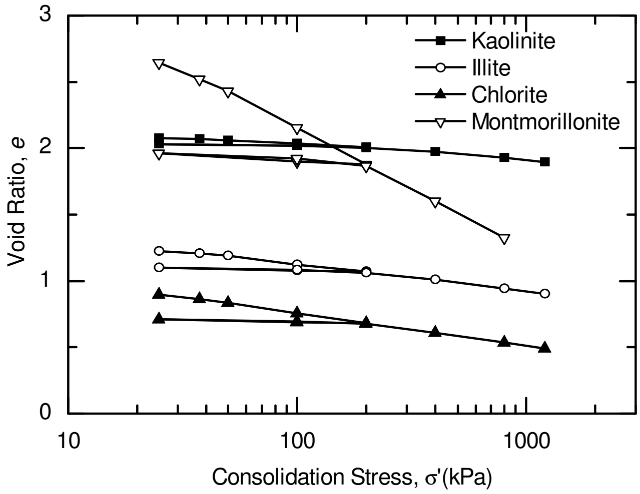


Figure 2 Void ratio versus consolidation stress for samples of Kaolinite, Illite, Montmorillonite and Chlorite

3.2 Compressive Properties of Mixtures of Kaolinite and Illite (K+I)

Figure 3 shows results of the oedometer tests performed on specimens of mixtures of Kaolinite and Illite. Due to the difference in liquid limits, these curves have different initial void ratios. The compression and swelling indexes were measured in the same way as described above. Figure 4(a) shows the evolution of the compression index with the content of illite for kaolinite and illite clay mixtures. The compression index increases nonlinearly with the illite content. It can be correlated by a non-linear interpolation function to the content of illite:

$$C_c = C_{cK} \times (1-\rho_I^{\alpha}) + C_{cI} \times \rho_I^{\alpha} \qquad (1)$$

where C_{cK} and C_{cI} are the values of the compression indexes for pure kaolinite and pure illite clays, respectively; C_c represents the compression index of the mixture; ρ_I is the mass percentage of illite; and α is the exponent of non-linearity. As shown in Figure 4(a), Eq.(1) becomes a linear interpolation for $\alpha = 1$. Based on the least squares method, $\alpha = 0.57$ was obtained corresponding to the best fitting for all the measured compression indexes.

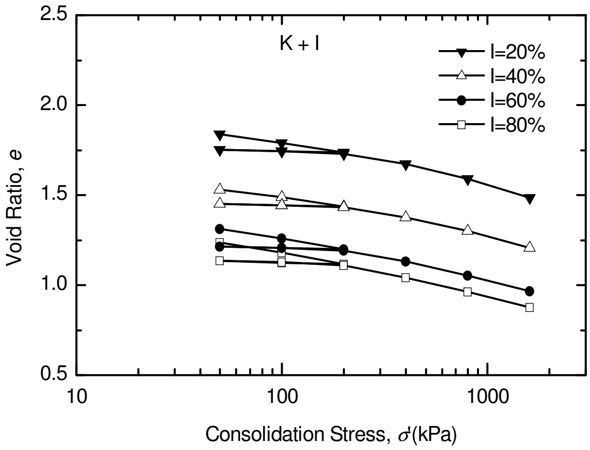


Figure 3 Void ratio versus consolidation stress for mixtures of Kaolinite and Illite

Figure 4(b) shows the evolution of the swelling index with the content of illite for kaolinite and illite clay mixtures. Eq.(2) extended from Eq.(1) by replacing C_c by C_s can be used to fit the swelling indexes of all the mixtures:

$$C_s = C_{sK} \times (1-\rho_I^{\alpha}) + C_{sI} \times \rho_I^{\alpha} \qquad (2)$$

where, C_{sK} and C_{sI} are the swelling indexes for pure kaolinite and pure illite clays, respectively; C_s represents the swelling index of the mixture. As shown in Figure 4(b), the swelling indexes of the clay mixtures increases with the content of illite; the non-linearity obtained by Eq(2) is more marked than the one obtained by Eq(1) with a higher value of $\alpha = 1.75$ corresponding to the best fitting.

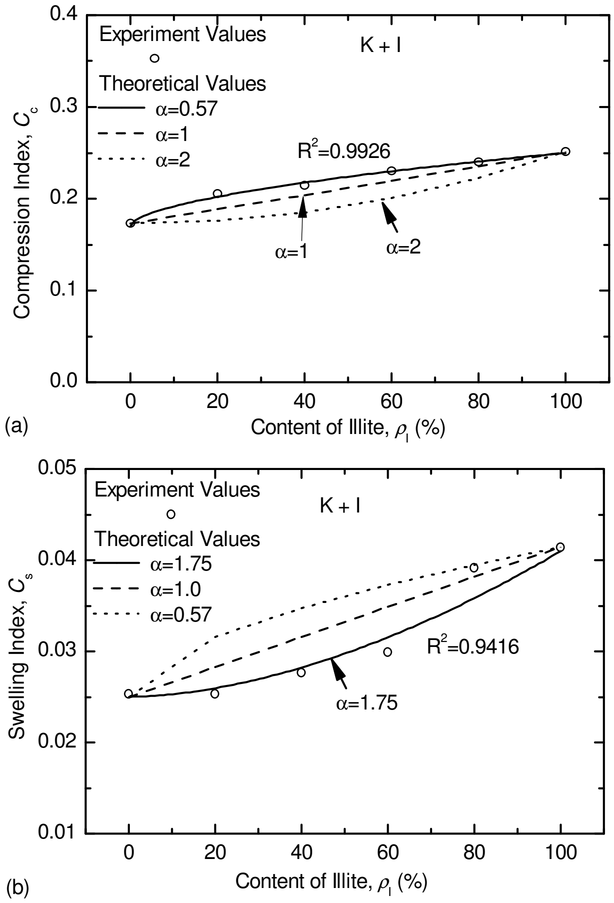


Figure 4 Evolution of compression properties with content of Illite clay for mixtures of Kaolinite and Illite: (a) compression index and (b) swelling index.

3.3 Compressive Properties of Mixtures of Kaolinite, Illite and Montmorillonite (K+I+M)

For clay mixtures of kaolinite, illite and montmorillonite, the results of the oedometer tests performed on clay mixtures for K/(K+I)=80% are shown in Figure 5 in order to illustrate the influence of montmorillonite content. The slope of the oedometer curves increases with the increase of the montmorillonite content. To quantify the influence of montmorillonite on the compression properties of kaolinite based clays, the compression and swelling indexes for all mixtures were measured. Figure 6(a) shows that the compression index increases with the content of montmorillonite when the same mass ratios of kaolinite to illite are kept. For the same content of montmorillonite, the compression index has almost no dependency with the content of illite, which demonstrates that montmorillonite is the dominant clay mineral for clay mixtures. By introducing the influence of montmorillonite in Eq.(1), we obtained

Eq.(3) which gives the expression of the compression index for this type of clay mixtures:

$$C_c = C_{cK} \times \left(1 - \rho_I^{\alpha} - \rho_M^{\beta}\right) + C_{cI} \times \rho_I^{\alpha} + C_{cM} \times \rho_M^{\beta} \tag{3}$$

where C_{cM} is the compression index of pure montmorillonite; ρ_M is the mass percentage of montmorillonite; and β is the exponent of non-linearity for the percentage of montmorillonite. Based on the least squares method, a value of β=0.8 was found for the best fitting for α = 0.57 estimated in the previous section.

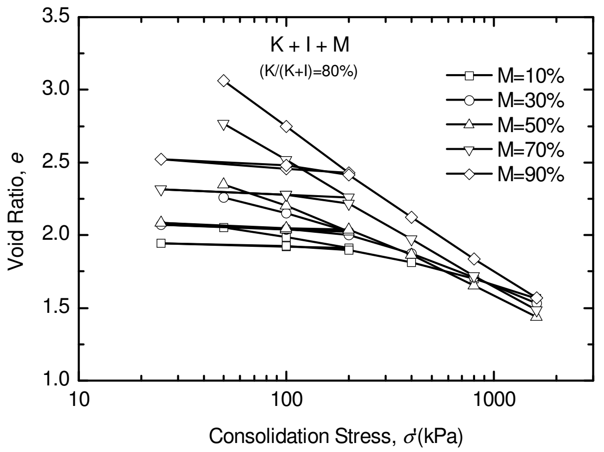


Figure 5 Void ratio versus consolidation stress for mixtures of Kaolinite, Illite and Montmorillonite for K/(K+I)=80%

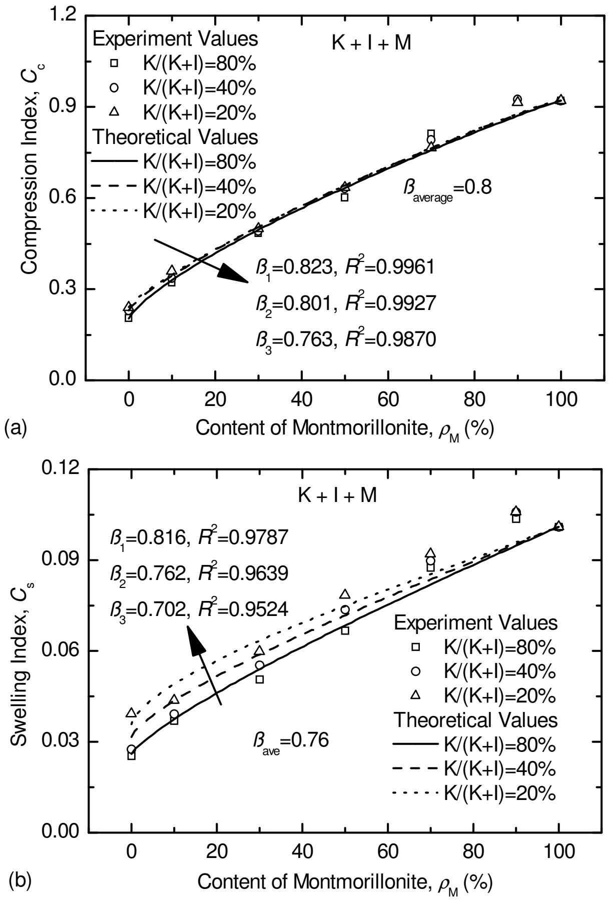


Figure 6 Evolution of compression properties with content of Montmorillonite clay for mixtures of Kaolinite, Illite and Montmorillonite: (a) compression index and (b) swelling index

For the swelling index of the clay mixtures, we adopted the same procedure, extending Eq.(2) by considering the influence of montmorillonite:

$$C_s = C_{sK} \times \left(1 - \rho_I^{\alpha} - \rho_M^{\beta}\right) + C_{sI} \times \rho_I^{\alpha} + C_{sM} \times \rho_M^{\beta} \tag{4}$$

where, C_{sM} is the swelling index of pure montmorillonite. A value of β = 0.76 was obtained by curve fitting and the same value of α = 1.75 was considered. As shown in Figure 6(b), under these conditions, Eq.(4) agrees reasonably well with the measured data.

The contribution of different pure clays to compression and swelling indexes can also be plotted in a triangle contour, as shown in Figure 7 based on experimental results. The effect of kaolinite and illite on the compression index is nearly the same, and the compression index has a steady increase with the content of montmorillonite. It can also be seen that an increase in the content of illite tends to increase the swelling index.

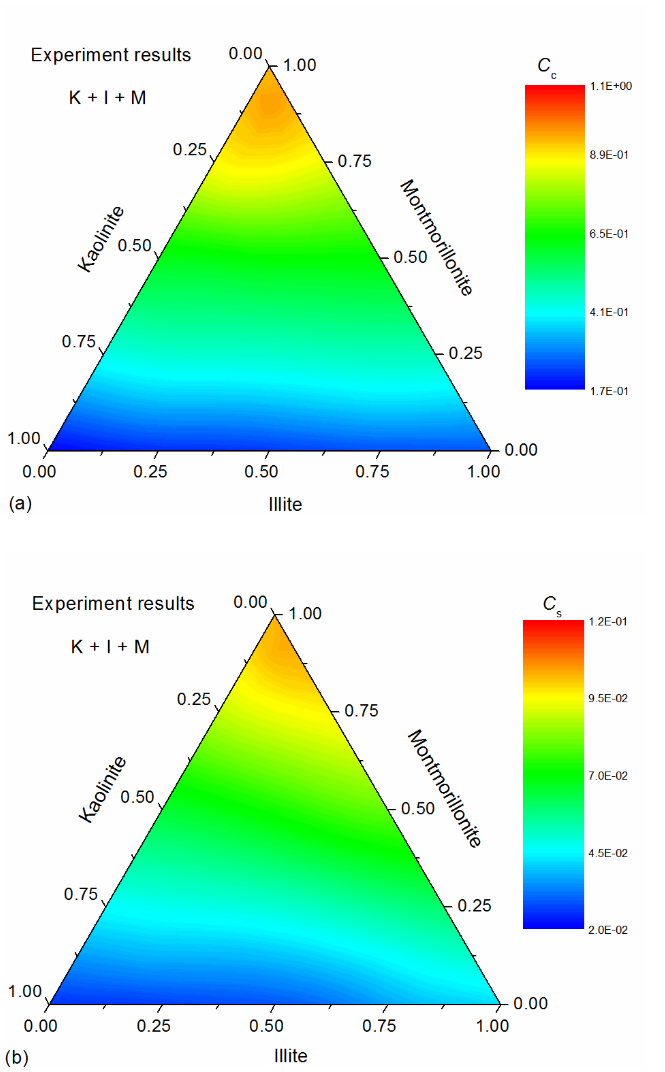
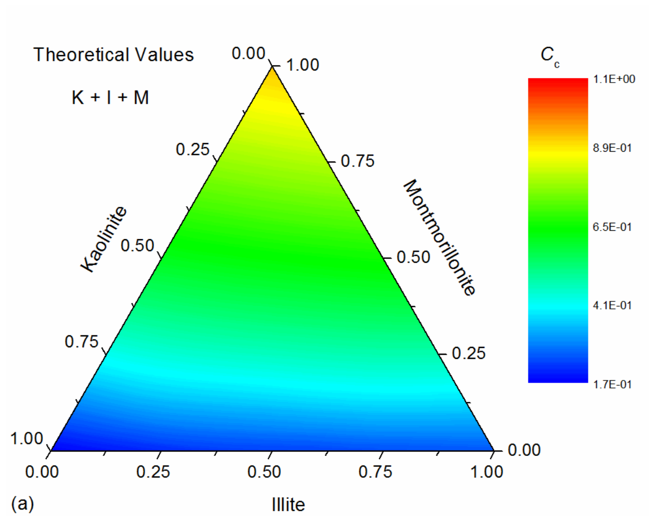


Figure 7 Triangle plot of experimental results for mixtures of Kaolinite, Illite and Montmorillonite for (a) compression index and (b) swelling index.

Similarly, according to Eq.(3) and Eq.(4), the theoretical contour for compression and swelling indexes can also be plotted (Figure 8). Compared to experimental contours, the proposed correlations can reproduce the overall trend of the contribution of each clay mineral in the mixture properties.



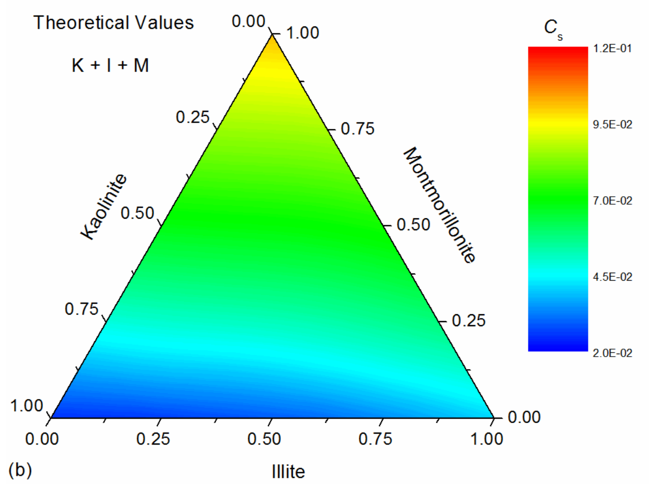


Figure 8 Triangle plot of theoretical results for mixtures of Kaolinite, Illite and Montmorillonite for (a) compression index and (b) swelling index

3.4 Compressive Properties of Mixtures of Kaolinite, Illite and Chlorite (K+I+C)

The compressive properties of mixtures of kaolinite, illite and chlorite can also be analyzed with the similar procedures as the ones used above. Figure 9 shows the results of the oedometer tests performed on clay mixtures of Kaolinite, Illite and Chlorite for K/(K+I)=80%. The oedometer curves have different initial void ratios, but their slopes are almost the same. Figure 10(a) shows that the compression index changes slightly with the content of chlorite. This is due to the small differences in the compression index among these three pure clays. By adding the influence of chlorite in Eq.(1), we obtained the relationship between the compression index of the mixture and the three pure clay contents:

$$C_c = C_{cK} \times \left(1 - \rho_I^{\alpha} - \rho_C^{\gamma}\right) + C_{cI} \times \rho_I^{\alpha} + C_{cC} \times \rho_C^{\gamma} \tag{5}$$

where C_{cC} is the compression index of pure chlorite; ρ_C is the mass percentage of chlorite; and γ is the exponent of non-linearity concerning the influence of the percentage of chlorite. The value γ=0.9 was found by best fitting, with α = 1.75.

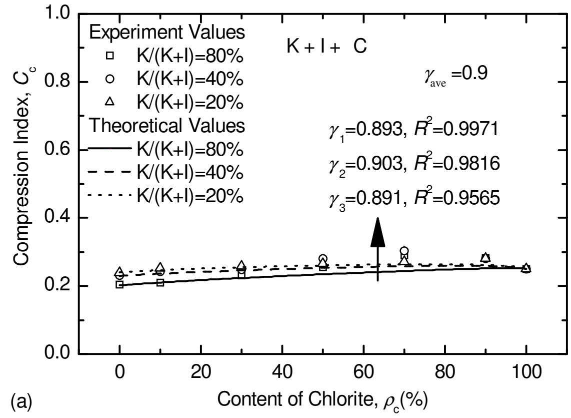
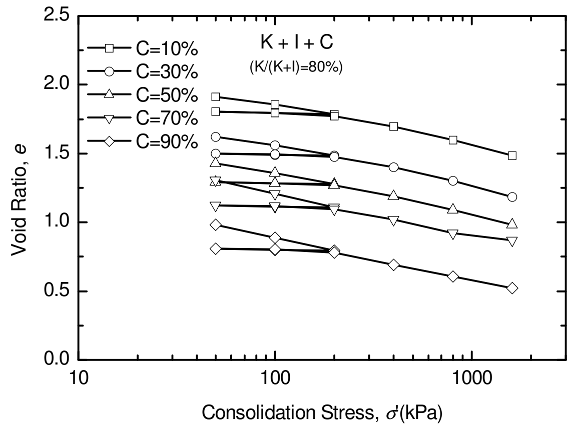


Figure 9 Void ratio versus consolidation stress for mixtures of Kaolinite, Illite and Chlorite for K/(K+I)=80%

Similarly, Eq.(6) can be used to estimate the influence of chlorite on the swelling indexes of the clay mixtures:

$$C_s = C_{sK} \times \left(1 - \rho_I^{\alpha} - \rho_C^{\gamma}\right) + C_{sI} \times \rho_I^{\alpha} + C_{sC} \times \rho_C^{\gamma} \tag{6}$$

where C_{sC} is the swelling index of pure chlorite. As shown in Figure 10(b), a value γ = 1.0 was estimated by best fitting, with α = 1.75.



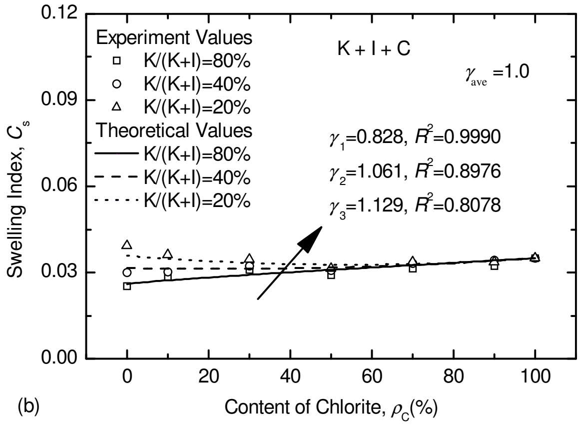


Figure 10 Evolution of compression properties with content of Chlorite clay for mixtures of Kaolinite, Illite and Chlorite: (a) compression index and (b) swelling index.

The contribution of different clay minerals to compression and swelling index values was also plotted in a triangle contour, as shown in Figure 11 based on experimental results for mixtures of kaolinite, illite and chlorite.

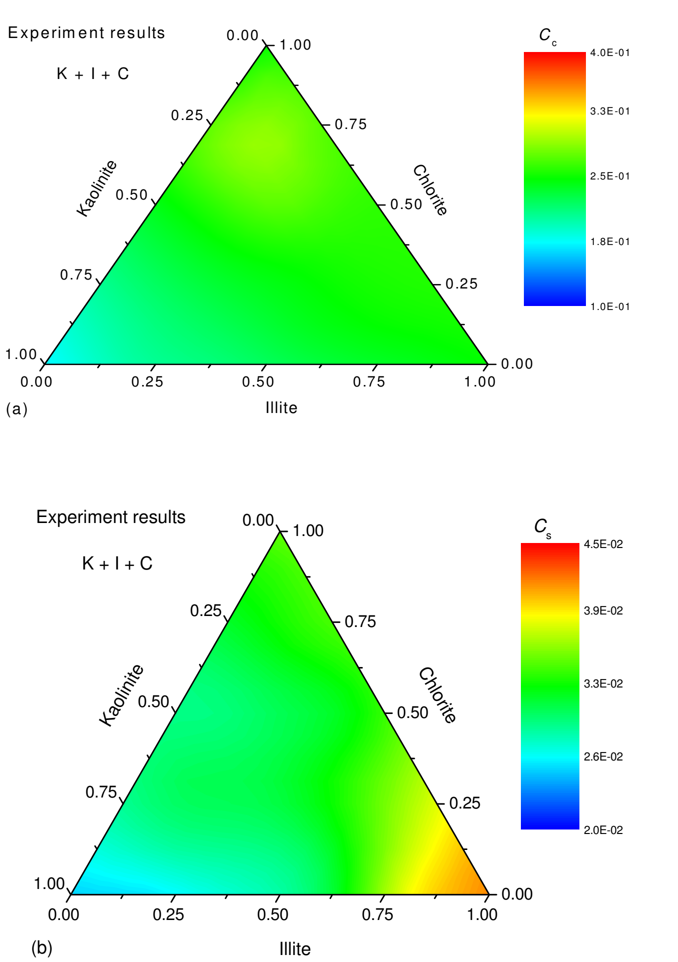


Figure 11 Triangle plot of experimental results for mixtures of Kaolinite, Illite and Chlorite for (a) compression index and (b) swelling index.

The values of the parameter α, β, γ in the expression of the compression and swelling indexes related to kaolinite based clay mixtures are summarized in Table 3.

Table 3 Values of parameters related to contribution of pure clays

Property	Illite α	Montmorillonite β	Chlorite γ
For compression index	0.57	0.8	0.9
For swelling index	1.75	0.76	1.0

Figure 12 illustrates the theoretical contours of compression and swelling indexes according to Eq.(5) and Eq.(6). Again, the proposed correlations reproduce the overall trend created by the contribution of kaolinite, illite and chlorite contents.

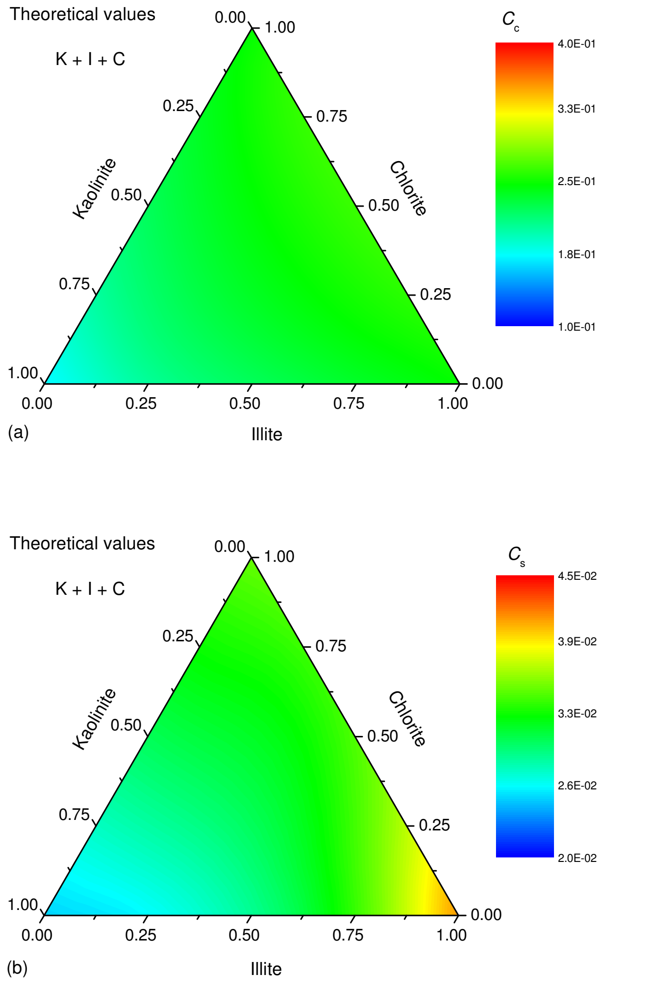


Figure 12 Triangle plot of theoretical results for mixtures of Kaolinite, Illite and Chlorite for (a) compression index and (b) swelling index.

4. VERIFICATION OF THE SUGGESTED CORRELATIONS

Adopting Eqs.(1)~(6), we can suggest the following correlations for compression and swelling indexes for general clay mixtures:

$$C_c = C_{cK} \times \left(1 - \rho_I^{\alpha} - \rho_M^{\beta} - \rho_C^{\gamma}\right) + C_{cI} \times \rho_I^{\alpha} + C_{cM} \times \rho_M^{\beta} + C_{cC} \times \rho_C^{\gamma} \quad (7)$$

$$C_s = C_{sK} \times \left(1 - \rho_I^{\alpha} - \rho_M^{\beta} - \rho_C^{\gamma}\right) + C_{sI} \times \rho_I^{\alpha} + C_{sM} \times \rho_M^{\beta} + C_{sC} \times \rho_C^{\gamma} \quad (8)$$

with the estimated parameters listed in Table 3.

In order to verify the validity of these correlations, conventional oedometer tests on mixtures of the four pure clays (K+I+M+C, see Table 2(d)) were conducted and the mechanical properties function of the contents in the different minerals were measured. Figure 13 shows the results of the oedometer tests performed on clay mixtures for C/(M+C)=20%. The initial void ratio of the mixtures and the slope of the oedometer test curves both increase with the increase of the contents of Montmorillonite and Chlorite. Figure 14 shows the evolution of the compression and swelling indexes versus the total content in montmorillonite and chlorite for both experimental and theoretical results using Eqs.(7)-(8). The comparison shows that the suggested correlations are suitable for describing the contribution of mineral contents on the compressive properties of clay mixtures

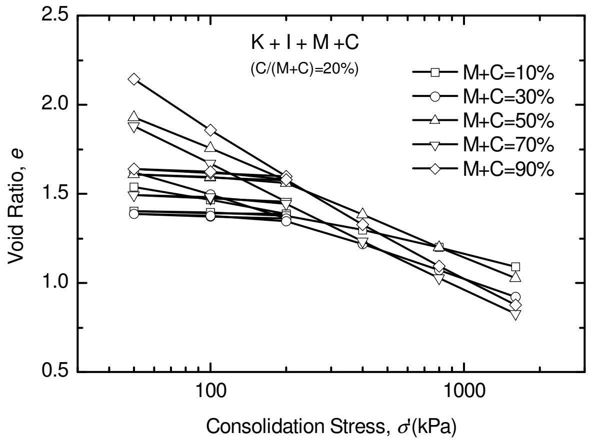


Figure 13 Void ratio versus consolidation stress for mixtures of four pure clay mixtures for C/(M+C)=20%

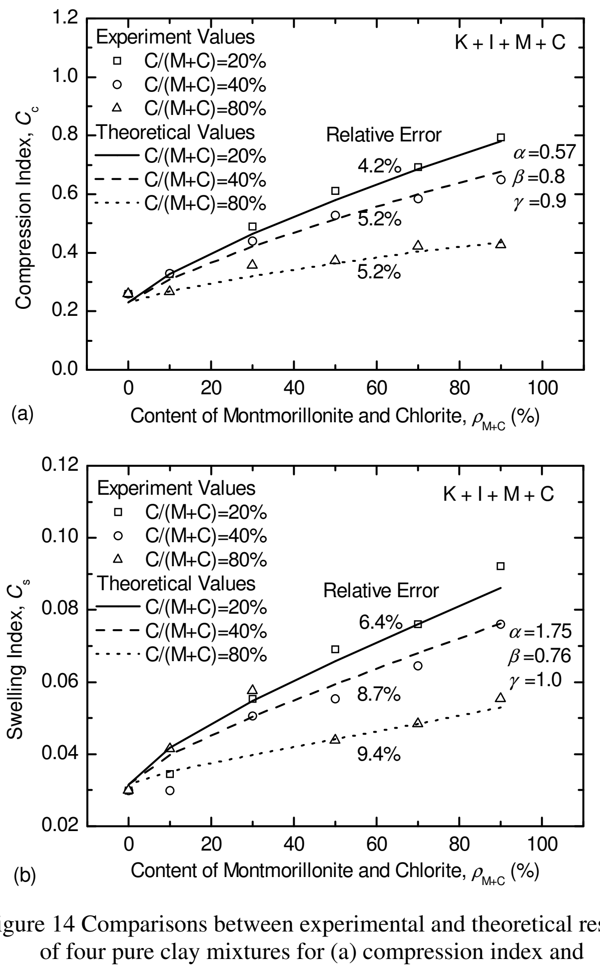


Figure 14 Comparisons between experimental and theoretical results of four pure clay mixtures for (a) compression index and (b) swelling index

5. CONCLUSIONS

By mixing various proportions of kaolinite, illite, montmorillonite and chlorite, 49 different soil specimens were prepared. Three series of conventional 1D-consolidation tests on two and three pure clay mixtures were conducted to obtain the compression and swelling indexes. For kaolinite based clayey soils, the relations between the compressive properties and the clay mineral content were analyzed based on the results obtained on samples with various contents of illite, montmorillonite and chlorite. Non-linear interpolation functions were suggested for the properties of these clayey soils. It could be concluded that the content in illite contributes positively (i.e. higher values of the compression and swelling indexes) to the compressive properties of the mixtures with a non-linearity parameter equal to 0.57 for the compression index and 1.75 for the swelling index; the content in chlorite contributes also positively with a non-linearity parameter equal to 0.9 for the compression index and 1.0 for the swelling index; the content in montmorillonite shows the most significant positive influence on the compression properties with a non-linearity parameter equal to 0.8 for the compression index and 0.76 for the swelling index.

The applicability of these correlations was verified with the test data obtained on mixtures of the four clay minerals.

Future studies will focus mainly on the comparison of natural clay properties with those obtained on these studied clay mixtures to continue investigating the impact of clay minerals on the mechanical properties of clayey soils.

6. ACKNOWLEDGMENTS

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