Consolidation behaviour of bentonite-kaolinite mix

Comportement de consolidation du mélange du bentonite-kaolinite

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ABSTRACT: Bentonite has a high affinity for water and swells many times its dry bulk volume. Its high swelling potential, small hydraulic conductivity and small particle size are used to advantage in the design and construction of landfill liners, slurry walls, grout curtains etc. However, the limited availability of high quality bentonite may be supplemented with bentonite-kaolinite mixes. This paper reports an investigation into the consolidation properties of such mixes. It was found that 50:50 mix of bentonite and kaolinite behaves nearly the same as bentonite in respect of compressibility and hydraulic conductivity and hence has the potential for replacing pure bentonite in clay liners and other similar applications. Investigation into bentonite mixes illustrates the significance of calcium-enriched environment on the increased hydraulic conductivity.

RÉSUMÉ: Bentonite, a une haute affinité avec l'eau et se gonfle plusieures fois de son volume sec en vrac. Sa haute potentiel en gonflement, sa faible conductivité hydraulique et sa petite taille granulometrique sont employées a l'avantage, dans la conception et construction des couches protectrices pour l'ensevelissement de déchets, murs de barbotine, des rideaux du coulis, etc. Cependant, la disponibilité limitée du Bentonite de haute qualité peut être supplémentée par lesun mélanges du Bentonite-Kaolinite. Cet article donne un compte rendu d'une étude sur les propriétés de consolidation dumélange du Bentonite-Kaolinite. Nous avons constaté qu'avec un mélange du Bentonite et Kaolinite, 50% de chaque en poids, se comporte comme le Bentonite pur, au pointe de vue de sa compressibility et de sa conductivité hydraulique. Le mélange pourrait bien replacer Bentonite pur pour fabriquer des couches protectrices en argile et pour des autres applications semblables. Les études effectués sur les mélanges de Bentonite montrent les effets significantifs d'un environment enriché en Calcium sur l'augmentation de sa conductivité hydraulique.

1 INTRODUCTION

Soil properties such as compressibility, hydraulic conductivity and shear strength depend on the soil minerals. Properties of a mixture (referred synonymously in this paper with 'mix') of soil minerals depend on the proportion of the minerals in the mix. As part of a study on hydraulic conductivity of bentonite in clay liners, an investigation was carried out to assess the potential success of using a mixture of clay. Geosynthetic clay liners are required to possess a hydraulic conductivity smaller than 10^{-11} m/sec by US EPA recommendation (Carson 1995). Therefore, to successfully replace bentonite in GCL with a mixture of clays, hydraulic conductivity must be checked. This paper presents the hydraulic conductivity and consolidation properties of mixes of kaolinite and bentonite based on a series of one-dimensional laboratory consolidation tests. Deduced values were carefully counterchecked with direct measurement using Rowe cells (Sinha et al. 2000). Compressibility and shear strength properties of the mix would also be different from those of bentonite. Consideration of shear strength of the mixes is beyond the scope of the present paper.

2 INDEX PROPERTIES

Index properties of Bentonite and Kaolinite used in this investigation are summarized in Table 1. The X-ray diffraction results showed that the bentonite used in this study contained mainly montmorillonite, and kaolinite contained mainly the mineral kaolinite. Bentonite (B) and Kaolinite (K) were oven dried at 105°C and mixed in dry condition at B:K weight ratios of 0:100, 10:90, 20:80, 30:70, 40:60, 50:50 and 100:0 for comparative purposes. Heating to 105°C is known to reduce the plasticity of bentonite (Grim, 1968). However, re-mixing of oven dried bentonite with water is expected to influence uniformly over the range of mixes used in this study and hence, the effect of heating on all the mixes may not be important. Table 2 shows the index properties of the Bentonite:Kaolinite mixes.

Table 1: Index properties of Bentonite and Kaolinite

Item	Standard	Bentonite	Kaolinite
Liquid limit, LL(%)	ASTM D4318	465	74
Plastic limit, PL (%)	ASTM D4318	41	34
Plasticity index, PI (%)	ASTM D4318	424	40
Specific gravity, G_s	ASTM D 854	2.77	2.64
Silt (2-74μm) (%)	ASTM D422	22	13
Clay (<2μm) (%)	ASTM D422	78	87
Cation Exchange Capacity (CEC) (meq/100g)		88	5

Table 2: Index properties of clay mixes

Bentonite (B) Kaolinite (K) Mix Ratio (B:K)	Liquid Limit LL (%)	Plastic Limit PL (%)	Plasticity Index PI (%)	Specific Gravity G_S
100:00	465.0	41.0	424.0	2.770
50:50	243.0	28.5	214.5	2.713
40:60	187.0	27.4	159.6	2.696
30:70	150.5	26.5	124.0	2.686
20:80	118.5	25.3	93.2	2.671
10:90	99.5	27.4	72.1	2.654
00:100	74.0	34.0	43.0	2.640

3 CONSOLIDATION TESTS

One-dimensional consolidation tests were carried out following BS1377:1990 on the clay mixes at their liquid limit using distilled water to determine the compressibility and swelling index. Hydraulic conductivity values were also deduced from these tests. Stainless steel rings of 70 mm diameter and 19 mm high were used for these tests. Axial compression was measured with

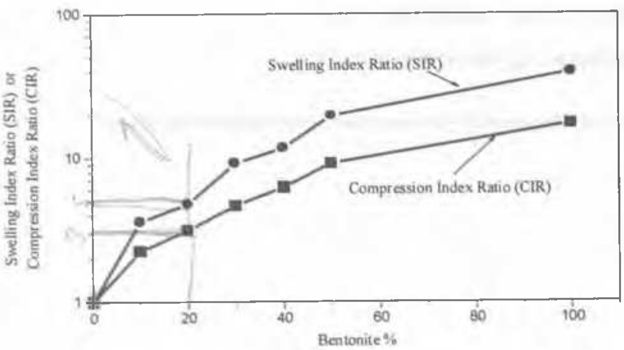

Figure 1. Variation of swelling index ratio (SIR) and compression index ratio (CIR) with bentonite percentage

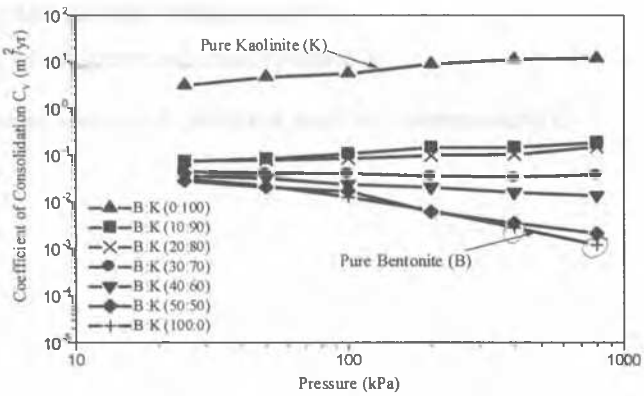

Figure 2: Coefficient of consolidation C_v vs pressure for bentonite-kaolinite (B:K) mixes

linear variable displacement transducers (LVDT) with 0.002 mm precision. Loading procedure consisted of the following stages. First, a seating pressure of 12.5 kPa was applied; secondly, the load was increased in stages to 100 kPa with load increment ratio of one. It was then unloaded to 25 kPa and finally reloaded up to 800 kPa with the load increment ratio of one.

The consolidation test results reveal that addition of only 10 percent bentonite can increase the compression index (C_c) and swelling index (C_s) of the mixes to about 2 and 3 times the respective values of pure kaolinite. Figure 1 shows the variation of Swelling Index Ratio (SIR) and Compression Index Ratio (CIR) with different bentonite percentages, where:

$$\text{Swelling Index Ratio (SIR)} = \frac{(C_s)_{mix}}{(C_s)_{kaolinite}} \quad (1)$$

$$\text{Compression Index Ratio (CIR)} = \frac{(C_c)_{mix}}{(C_c)_{kaolinite}} \quad (2)$$

It is clear that with about 30% bentonite in the mix the C_s value changed by about 10 times, while about 50% bentonite changed the C_c value by about 10 times. It may also be viewed that mixing with Kaolinite could substantially reduce swelling and compressibility characteristics of bentonite.

Addition of bentonite also reduces the coefficient of consolidation (C_v), which implies that the clay mix will require longer time as compared to kaolinite for consolidation process. C_v values of different bentonite:kaolinite (B:K) mixes are shown in Figure 2. It is observed that the C_v increases with pressure for pure kaolinite, whereas the C_v variation with pressure has a decreasing trend in pure bentonite. This is consistent with the findings of Samarasinghe et al. (1982). For B:K mix of 20:80, the C_v remains virtually constant with pressure. With B:K=30:70 mix and for larger bentonite proportions, C_v variation begins to show a decreasing trend with pressure. Figure 2 also reveals that addition of 10% bentonite can reduce the C_v by more than 10 times as compared with C_v of pure kaolinite. C_v variation with pressure for a 50:50 mix is practically identical to that of pure bentonite.

The coefficient of volume compressibility (m_v) decreased steadily with increased pressure for all B:K mix ratios as shown in Figure 3, which also reveals that m_v value increases with increased percentage of bentonite for all pressures. It can be viewed that replacement of bentonite with kaolinite mix assists in the reduction of m_v, which is useful in mitigating excessive ground settlement. Values of hydraulic conductivity or coefficients of permeability (k_v) were deduced from m_v and C_v values.

It appears that being very fine, about 40 to 50 montmorillonite particles in bentonite may occupy the large pore space between two kaolinite particles in a B:K 50:50 mix. Therefore the reduction in hydraulic conductivity seen in kaolinite in Figure 4, as the bentonite proportion is increased in the mix, can be ex-

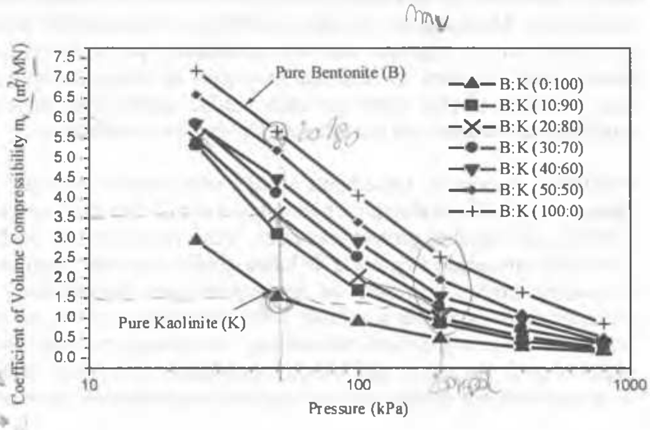

Figure 3: Coefficient of volume compressibility m_v of bentonite-kaolinite (B:K) mixes

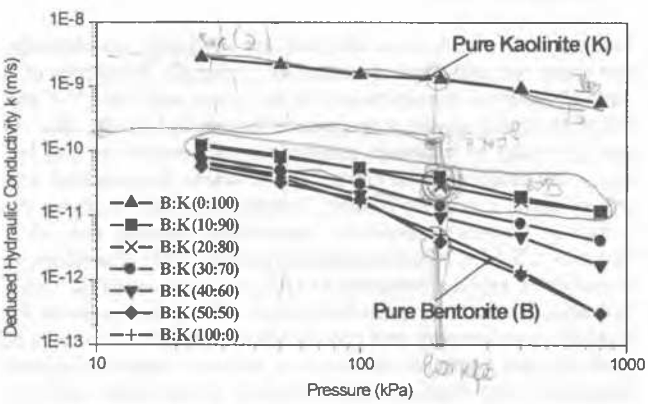

Figure 4: Deduced hydraulic conductivity k_v vs pressure for Bentonite-Kaolinite (B:K) Mixes

plained by the hypothesis of montmorillonite particles occupying the pore space between kaolinite particles (Sinha 2000).

The variation of k_v with pressure for different mixes is shown in Figure 4. Comparing k_v value at B:K of 0:100 and 10:90, it can be seen that addition of 10% bentonite can reduce the pure kaolinite hydraulic conductivity by more than 10 times. A B:K mix of 50:50 is almost indistinguishable from the pure bentonite hydraulic conductivity. This 50:50 mix is considered to be the threshold mix ratio (Ahmad et al. 2000).

3.1 *Liquid limit and Swell index of B:K mixes with different permeants*

Swell index tests and liquid limit tests were carried out with permeants 0.1M sodium hydroxide, 0.1M hydrochloric acid, and 0.25M calcium chloride for bentonite, B:K=50:50 mix and kao-

Table 3. Variation of liquid limit (%) with different permeants

Permeant	Kaolinite	50:50 Bentonite Kaolinite	Kaolinite
Distilled water	74.0	243.0	465.0
0.25M Calcium chloride	66.8	90.0	127.0
0.1M Hydrochloric acid	76.4	150.0	257.0
0.1M Sodium hydroxide	51.5	285.0	502.0

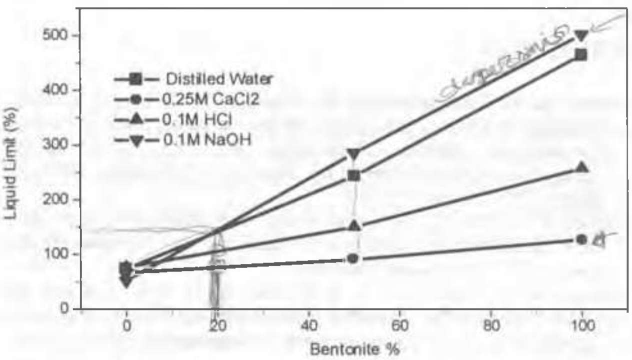

Figure 5. Variation of liquid limit with bentonite content under different chemicals

linite. Table 3 shows the variation of liquid limit of kaolinite, bentonite and the 50:50 mix of bentonite and kaolinite when mixed with these permeants. Figure 5 shows the variation of liquid limit with bentonite percentage and Figure 6 shows the variation of swell index. It was found that 0.25M calcium chloride reduced the liquid limit and swell index significantly compared to distilled water. Sodium hydroxide (0.1M) actually increased these values but decreased in the case of pure kaolinite. With 0.1M hydrochloric acid the situation was intermediary between the above values but lower than that with distilled water.

3.2 *Hydraulic conductivity (k) measurement using consolidation cells*

Direct hydraulic conductivity tests were carried out on pure kaolinite, B:K=50:50 mix and pure bentonite in Rowe consolidation cells using distilled water as the permeant. For $CaCl_2$, HCl and NaOH permeants, fixed ring consolidation cells made with perspex were employed to overcome chemical corrosion in metallic cells. A burette attached to the base of the consolidation cell enabled the determination of the hydraulic conductivity using the falling head method. The test results indicated that calcium chloride permeant caused an increase in the hydraulic conductivity by about 4.5 times in kaolinite, 16 times in B:K=50:50 mix and 34 times in bentonite. Figures 7 and 8 show typical observations in a Rowe cell and an oedometer cell with the constant head method and falling head method respectively. Figure 9 shows the variation of hydraulic conductivity in kaolinite, B:K=50:50 mix and bentonite compared with distilled water and calcium chloride.

Hydraulic conductivity measured with distilled water as permeant is used as the basis for comparison. In the acidic environment of hydrochloric acid, it was found that the hydraulic conductivity of kaolinite increased by 9.25 times, whereas for B:K mix of 50:50 the increase was 2.5 times. The reduction observed in the liquid limit and swell index, which are simple geotechnical laboratory tests, can be used as a pointer that the leachate was changing the properties of clay which may eventually lead to increased hydraulic conductivity.

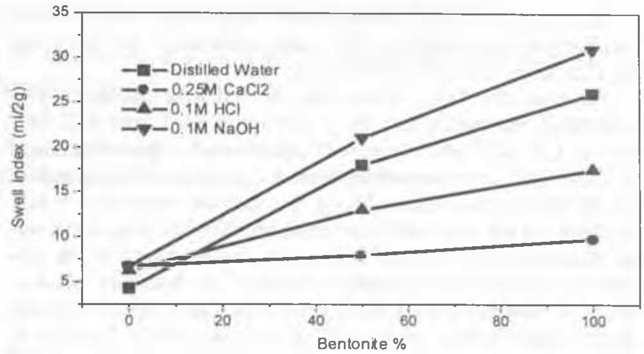

Figure 6. Variation of swell index with bentonite under difference chemicals

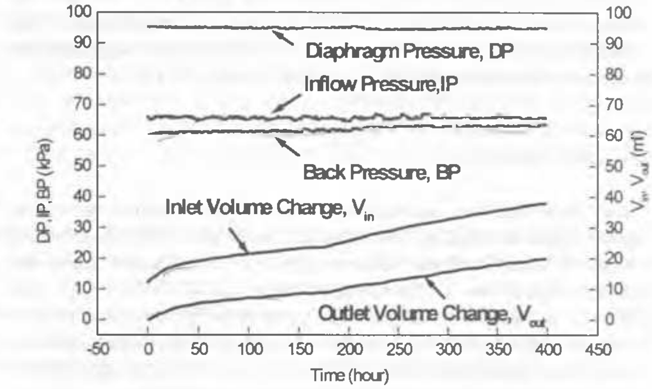

Figure 7. Determination of hydraulic conductivity k (m/s) with the constant head method in Rowe cell (Permeant: distilled water, Consolidation pressure: 35 kPa, B:K=50:50 mix)

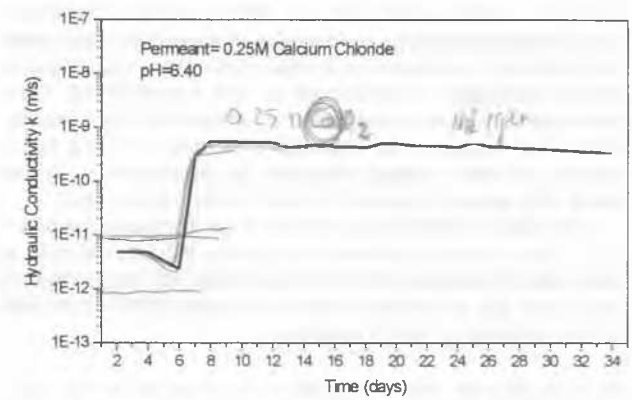

Figure 8. Variation of hydraulic conductivity k (m/s) with time using falling head method (Permeant: 0.25M $CaCl_2$, Consolidation pressure: 35 kPa, B:K=50:50 mix)

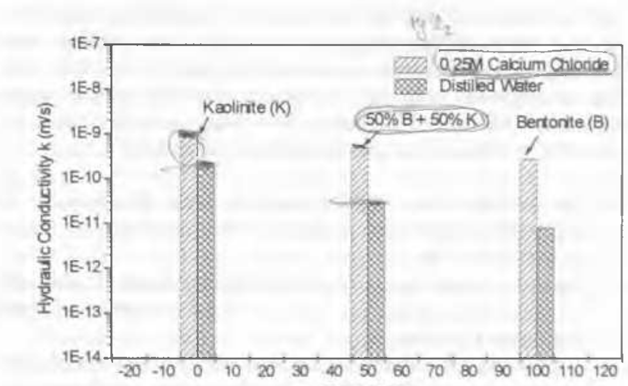

Figure 9. Variation of hydraulic conductivity k (m/s) in B:K mixes using falling head method. (Permeant: distilled water and 0.25M $CaCl_2$, Consolidation pressure: 35 kPa)

In the case of 0.1M sodium hydroxide (NaOH) the hydraulic conductivity increased by 1.62 times in kaolinite but decreased by 1.26 times in the B:K=50:50 mix.

Gleason et al. (1997) found that the hydraulic conductivity of powdered bentonite (LL= 590 to 603) increased from 6 X 10^{-12} m/s to 1 X 10^{-10} m/s - nearly 17 times - under the influence of 0.25 M $CaCl_2$ compared with Austin tap water having a pH of 10. In the current series of tests, the distilled water (pH = 6.8) perhaps did not have sufficient ionic activity like Austin tap water. However as it was free from strong ionic activity it was considered suitable for comparative studies. The hydraulic conductivity of bentonite shown in Figure 9 with $CaCl_2$ solution is very much similar to the results of Gleason et al. (1997). Lentz et al. (1984) reported that hydraulic conductivity of kaolinite with HCl of pH=1.0 was about 1.0 x 10^{-9} m/s, which was in the same order as the value for HCl acid solution with pH=1.40. He also reported that the hydraulic conductivity value for kaolinite using NaOH at pH=13.0 was about 4 X 10^{-10} m/s, which was similarly very near the value for NaOH solution with pH=13.1.

4 DISCUSSION

The consolidation properties of bentonite-kaolinite mixes reported above illustrate an important behavior of mixes in which a given characteristic feature gradually transforms form the value of one clay to the corresponding value of the other clay. The variation is not, in general, linear with the concentration of clay. Knowledge of the gradation of change in the characteristics would be beneficial in the mitigation of undesirable qualities of one clay by replacement with a mixture of two clays.

The high compressibility and swelling characteristics of bentonite rich soils could be greatly reduced, as part of ground improvement work, by suitably mixing with less active sols such as kaolinite or even quartz sand or forming columns with such soils. Similarly hydraulic conductivity of some type of soil could be reduced by incorporating a small percentage of bentonite at appropriate stages of construction, as with bentonite clay liners, for example, without unduly affecting compressibility characteristics. Only caution to be exercised is the need to watch for reduction of shear strength that may be detrimental in certain cases. This aspect is beyond the scope of the present paper.

The effect of different permeants on the hydraulic conductivity of clays is very important, as seen by calcium chloride on bentonite. The increase in hydraulic conductivity in geosynthetic clay liners due to calcium-enriched environment is of considerable importance in landfill operations.

5 CONCLUSIONS

Based on the individual and mixed clay properties of kaolinite and bentonite reported in this paper, it is possible to institute a ground improvement program to mitigate undesirable compressibility and hydraulic conductivity of clays by suitably mixing the given soil uniformly or perhaps discreetly with an appropriate soil of desired property. This study with the two clays used in the tests leads to the following conclusions:

1. The swelling index (C_s) increased by about 10 times for the bentonite-kaolinite mix ratio of 30:70, compared with that of the pure kaolinite.
2. The compression index (C_c) increased by about 10 times for the bentonite-kaolinite mix ratio of 50:50, compared with that of the pure kaolinite.
3. A minimum of 30% bentonite was needed in the bentonite-kaolinite mix to show the same decreasing trend in C_v as shown by the pure bentonite.
4. A 10% bentonite in the bentonite-kaolinite mix can reduce the coefficient of consolidation (C_v) and coefficient of permeability (k_v) by more than 10 times compared with the pure kaolinite.
5. Bentonite-Kaolinite mix of 50:50 behaved almost the same as pure bentonite in respect of C_v and k_v. Hence it is apt to be termed as the threshold mix ratio.
6. A hypothesis of fine particles occupying the pore space of larger particles seems to explain the reduction observed in the hydraulic conductivity of kaolinite clay upon bentonite mixing.
7. Calcium-enriched environment could increase the hydraulic conductivity of bentonite, which should be taken into account in geosynthetics clay liner design.

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