Investigation of Shrinkage and Swelling Behaviour of Expansive/Non-Expansive Clay Mixtures

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ABSTRACT: This paper presents an investigation of physical and engineering properties of expansive clays prepared by reconstituting Na-montmorillonite bentonite mixed with natural non-swelling Bangkok clay. The Bangkok clay contents were varied to 0, 20, 40, 60, 80 and 100% by weight. This investigation aims at highlighting the influence of the non-swelling clay content on physical and mechanical properties of the mixture by paying particular attention to its effect on shrinkage and swelling potential. The basic physical properties were determined, along with the unconfined compression, oedometer, compaction and CBR characteristics. The linear shrinkage bar tests and swelling tests were also performed to observe the areal shrinkage and vertical swelling strains. In addition, a microstructure investigation was conducted through X-Ray diffractometer (XRD) and scanning electron microscope (SEM) observations. By increasing the Bangkok clay content in the mixture clays, the compressive strength and CBR values were markedly increased, while the plasticity and the swelling and shrinkage strains were reduced significantly. Correlations were established between the index properties and other properties such as the maximum dry density (MDD), the optimum moisture content (OMC), the CBR, the compression index (C_c), and the swelling index (C_s). These correlations were tested against data from some previous studies on other soil types including natural expansive clays and found to be applicable satisfactorily in most cases. It was also found that a relatively large increase of non-swelling clay content is necessary to obtain markedly larger strength, while the plasticity is greatly reduced by a minor increase. The above findings will be useful in designing earth works where locally occurring expansive clays are desired to be used with minimum improvements.

Keywords: Shrinkage, Laboratory tests, Expansive soil, Bentonite, Bangkok Clay

1. INTRODUCTION

Expansive clays exist in many places in the world, being particularly noticeable recently in some Asian countries such as India (Katti et al., 2002; Shelke and Murty, 2010), China (Ramaswamy and Anirudhan, 2009), Banglasdesh (Siddique and Hossian, 2013), Indonesia (Java, Sumatra, and Sulawesi) (Bukit et al., 2013), and Thailand (Sawangsuriya et al., 2011). They were often formed from volcanic ashes by in-situ alteration through hydrothermal processes. Expansive clays' features, the significant volumetric expansion upon wetting and shrinkage upon drying, are a very common cause of problems which have long been recognised in these clays because they could cause failure of structures constructed above them (Louafi and Bahar, 2012; Puppala et al., 2013; Lim et al., 2013). The damages are mainly on building foundations (Dasgupta, 2013), slopes (Zhan et al., 2006), roadway subgrades (Muntohar, 2006), highways, airports seaports and other residential buildings (Ramadas et al., 2012).

Because of the variation of water content or suction in the ground, expansive clays experience changes in volume. Such volume changes and resulting shrink-swell movements often distress the infrastructure that is not designed to resist those swelling pressures or forced movements (Sudjianto et al., 2011). Shrinkage characterisation of expansive clays was attempted by Puppala et al. (2006), among others, on natural and stabilised expansive clayey soils using two different measurement methods, manual and digital imaging which focused on linear and three-dimensional volumetric shrinkages.

The swelling pressures depend on the loading and wetting conditions as a consequence of the different microstructure changes that occur under different conditions (Wang et al., 2012). Wetting of expansive clays causes such a great uplift force that suppressing their actions on structures purely by mechanical means (with piles and rigid linings, for example) is not a realistic option. An ultimate countermeasure would be a total replacement of problematic expansive clays with non-expansive ones. However, it will be more practical and cost-effective to alleviate the expansive characteristics by mixing the clays in problem with less active, non-expansive soils at an appropriate ratio, thus limiting the amounts of both newly purchased soils and surplus soils that would be generated upon full replacement. If added soils have a cementing effect, it is considered to be more advantageous in restricting the swelling. This paper focuses on the 'diluting' effects of adding a non-expansive clay on expansive characteristics of an expansive clay, while the authors' ongoing research also considers cementation as an additional variable.

This study attempts to show and characterise the influence of the non-swelling clay content on physical and mechanical properties of the swelling clay by paying particular attention to its effect on swelling and shrinkage potential. To approach the above objectives, an artificial expansive clay, Na-montmorillonite bentonite mixed with natural non-swelling Bangkok clay, was prepared either by reconstitution or compaction. A number of experiments were performed on both physical and mechanical properties of the artificial expansive clay, including the Atterberg limits, specific gravity, gradation, compaction, CBR characteristics, unconfined compression strength, swelling and linear shrinkage behaviour. X-ray diffractometer (XRD) and scanning electron microscope (SEM) observations were also conducted to identify the mineral compositions and observe particle arrangements.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this study were a natural Bangkok clay and a commercial Na-montmorillonite bentonite which is locally produced in Thailand. The Bangkok clay is well-known as soft marine silty clay lying beneath the low flat plains of the central area of Thailand (Seah and Lai, 2003; Naga et al., 2005; Horpibulsuk et al., 2011; Surarak et al., 2012), characterised by a high water content, low shear strength, and high compressibility (Sunitsakul et al., 2010; Surarak et al., 2012). According to Mitchell and Soga (2005), Prikryl (2006), and Poulose et al., (2013), Na-montmorillonite bentonite is a high swelling clay composed mainly of Na-montmorillonite which is the result of chemical alteration of igneous materials (usually tuff or volcanic ash). Montmorillonite has low permeability and marked expansibility due to stacked lamellae each of which consists of two sheets of SiO_4 tetrahedrons sandwiching an octahedral layer of hydroxyls and Fe, Mg or Li ions (Pusch and Yong, 2006). Observed by the XRD, the chemical compounds of Bangkok clay and Na-montmorillonite bentonite used in this study were identified as summarised in Table 1.

Table 1 Percentage of chemical compounds from XRD results of bentonite and Bangkok clay

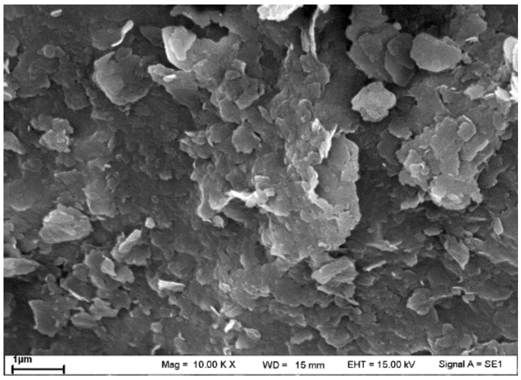
Chemical compounds	**Bentonite (%)**	**Bangkok Clay (%)**
Quartz (SiO_2)	50	63
Aluminum oxide (Al_2O_3)	19	21
Iron oxide (FeO)	15	8
Calcium oxide (CaO)	5	-
Magnesium oxide (MgO)	3	2
Potassium oxide (K_2O)	-	3
Sodium oxide (Na_2O)	3	1
Other minerals	5	3

According to the literature (Seah and Lai, 2003; Naga et al., 2005; Horpibulsuk et al., 2011; Surarak et al., 2012), Bangkok clay is a low-swelling clay exhibiting physical and engineering properties similar to those of kaolin, while bentonite is a clay with a high swelling potential. Figure 1 shows SEM photographs of Bangkok clay and bentonite with a 1 μm scale bar. Based on these images, clear shapes and particle arrangements of the Bangkok clay and bentonite can be identified. It is observed that the particles of Bangkok clay in Figure 1(a) are separated from each other while those of the bentonite are stacked together to form as a thicker flake structure as shown in Figure 1(b). Mitchell and Soga (2005) stated that there is some concentration of different clay minerals' particle sizes within certain ranges smaller than 2 μm, as indicated in Table 2.

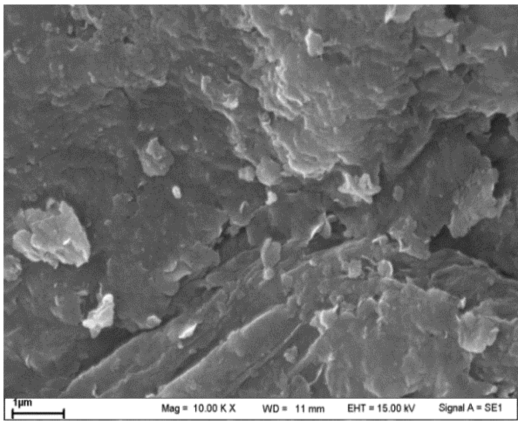
Table 2 Mineral composition of different particle size ranges in soils (after Mitchell and Soga, 2005)

Particle size (μm)	**Predominating Constituents**	**Common Constituents**	**Rare Constituents**
0.1	Montmorillonite Beidellite	Mica intermediates	Illite(traces)
0.1-0.2	Mica inter mediates	Kaolinite Montmorillonite	Illite Quartz (traces)
0.2-2.0	Kaolinite	Illite Mica intermediates Micas Halloysite	Quartz Montmorillonite Feldspar
2.0-11.0	Micas Illites Feldspars	Quartz Kaolinite	Halloysite (traces) Montmorillonite (traces)

The primary mineral existing in bentonite is montmorillonite (typically 60-90%) (Lee and Shackelford, 2005). Hanus et al., (2006) suggested that water absorption is a characteristic behaviour of material showing high specific surface and cation exchange capacity. According to Nelson and Miller (1992), the specific surface area of montmorillonite is very large (700-840 m^2/g) compared to those of the kaolinite (10-20 m^2/g) and of other clay minerals. In clays with larger specific surface area, water is strongly attached to the clay mineral surfaces, and leads to higher plasticity, whereas those with smaller specific surface area do not develop significant plasticity even in finely ground soils (Mitchell and Soga, 2005). The higher specific surface area of montmorillonite is thus linked to larger potential of swelling and shrinkage via increased plasticity.



(a)



b)

Figure 1 SEM photographs, (a) Bangkok clay and (b) Bentonitewith 1 μm scale bar

2.2 Engineering Properties

The index properties of bentonite and Bangkok clay mixture were determined according to the ASTM standard method. Those are Atterberg limits (ASTM D4318), specific gravity (ASTM D854-10), and grain size distribution (ASTM D422-63). They are summarised in Table 3.

Figure 2 presents the particle size distributions of pure bentonite and Bangkok clay. The bentonite has 57% clay fraction (i.e. smaller than 2 μm) while the Bangkok clay's is 76%. The aggregation of the Bentonite particles observed in Figure 1(b) explains why the predomantly Illitic Bangkok clay has the apparently finer particle distribution than the montmorillonite bentonite.

Table 3 Index properties of the bentonite-Bangkok clay mixtures

Index properties	**Bangkok clay content (%)**					
	0	20	40	60	80	100
Liquid limit, LL (%)	509	309	281	191	102	72
Plastic limit, PL (%)	54	50	42	39	37	31
Shrinkage limit, SL (%)	23	22	12	12	16	14
Plasticity index, PI	455	259	239	152	65	41
Specific gravity, G_s	2.87	2.82	2.78	2.76	2.69	2.64
Activity, A (-)	8.0	4.3	3.7	2.2	0.9	0.5

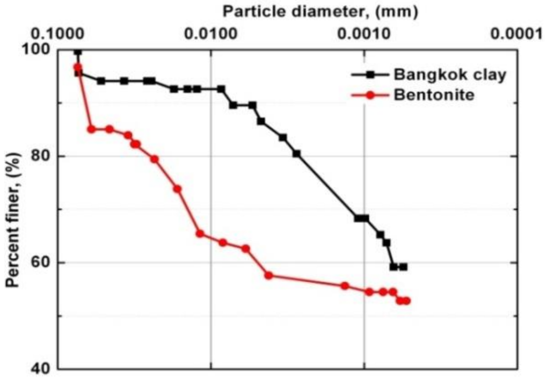


Figure 2 Grain size distributions of bentonite and Bangkok clay

2.3 Sample Preparation and Testing Methods

2.3.1 Sample Preparation

In this study, large consolidometer was used to prepare reconstituted samples with dimensions of 160mm in diameter and 300mm in height. Bangkok clay was firstly air-dried, powdered and sieved through No. 40 sieve (425μm) similarly to Tanaka and Kamei (2011), who studied reconstituted Ariake clay. The Bangkok clay powder was mixed with the bentonite powder by a mixer, adding an appropriate amount of water (approximately to reach the liquidity index of 1.5) to prevent segregation or bleeding.

After being mixed to be completely uniform, the slurry was placed into the large consolidometer chamber and an initial vertical stress of 5 kPa was applied. The stress was increased to a maximum vertical stress of 30 kPa with an increment of 5 kPa. For each load increment, the load was maintained until the full dissipation of pore water pressure within the sample has been achieved. After completing the loading steps, the clay cake was extruded from the chamber by using a hydraulic jack, and then the clay cake was trimmed into smaller pieces for subsequent tests.

2.3.2 Compaction and CBR Test

The compaction and California Bearing Ratio (CBR) tests were performed on the bentonite-Bangkok clay mixture as specified in Table 3. The purpose was to identify the compaction and CBR characteristics and their variation trend according to different soil composition and resulting plasticity.

In this investigation the compaction tests followed the modified routine (ASTM D1557-00). The CBR tests were performed on samples compacted at the optimum moisture content (OMC) and the maximum dry density (MDD), following the ASTM D1883-99. The compacted samples, still in the moulds, were soaked for 65 days in a big tank filled with water to simulate its wetted and hence possibly weakened conditions in the field. The CBR values were measured both for soaked and unsoaked specimens.

The expansions of the samples were measured in the vertical direction during soaking by a dial gauge installed at the top of the soaking specimen to quantify the vertical swelling strain during soaking under a surcharge of 2.5 kPa. The surcharge was applied on the top surface of the specimen to represent the weight of pavement above the subgrade following ASTM D1883-99.

2.3.3 Oedometer Test

In order to evaluate the compressibility and the volume change characteristics of the expansive clays at saturated, high-water content states, one-dimensional compression and swelling were conducted on reconstituted samples of the mixture clays in standard oedometers (ASTM D2435-03). The samples, taken after pre-consolidation in the consolidometer, had various initial water contents ranging from 60% to 372%, slightly smaller than their liquid limits of 72% to 509% (Tables 3 and 6), respectively.

2.3.4 Unconfined Compression Test

A series of unconfined compression tests (UC) was performed on the reconstituted samples by following the ASTM D2166-00. The tests were performed immediately after removing the samples from the consolidometer chamber. The samples were prepared by trimming to the dimensions of 50mm in diameter and 100mm in height and then tested at a loading rate of 0.75mm/min.

2.3.5 Linear Shrinkage Bar Test

To measure of the shrinkage behvaiour of swelling clay, it could be referred to the one-dimensional expansion and shrinkage test (ASTM D3877-96) and the linear shrinkage test (BS 1377). However, a linear shrikage bar test was suggested by Puppala et al. (2004, 2006, and 2007) incooperated with image processing technique. According to Puppala et al. (2006) using image processing technique could provide more accurate measuring results than that from the manual measurement. Therefore, the linear shrinkage bar test with image processing technique was selected in this study. The mixtures of bentonite and Bangkok clay were uniformly mixed with water at their liquid limits (LL) and placed in a 120mm x 20mm x 5mm mould. The clay specimens in the mould were initially air-dried at a controlled temperature room of 30 ± 1^{o}C and a relative humidity of 50 ± 2 %. The specimens were kept until it reached stable moisture content by the room-air dry. After drying, cracks formed in the soil specimens in irregular patterns as shown in Figure 3. Photographs of the whole sample were taken by using a digital camera. Then an image processing was adopted to determine the areal shrinkage strain of soil specimen. The image analysis provided both cracked and uncracked areas as reflected by black and white pixels relatively, after binarisation with an appropriately selected threshold. By taking the ratio of cracked areas (area of void) after air-drying (A_c) to original area (area of sample before being cracked) of the sample (A_t), areal shrinkage strains were determined (Puppala et al. 2004).

$$\text{Areal shrinkage strain} = \frac{A_c}{A_t} \qquad (1)$$

Figure 3(A) and 3(B) show the Bangkok clay and the bentonite before and after 5 and 7 days of air-drying, respectively, while Figure 3(c) shows the image thresholding after air-drying.

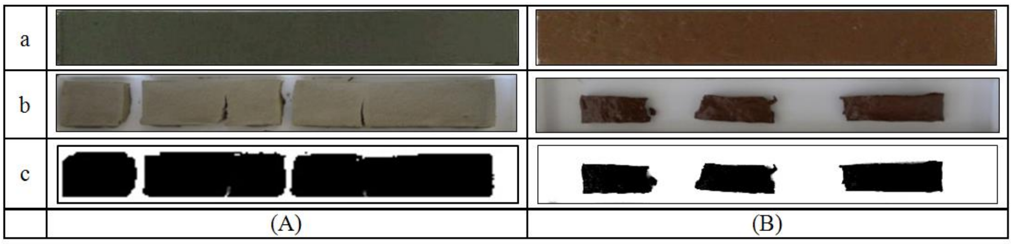


Figure 3 Linear shrinkage bar test (A) Bangkok clay, (B) Bentonite (a = before air-dried, b = after air-dried, c = binarised to black and white after image thresholding on air-dried specimens)

3. RESULTS AND DISCUSSIONS

3.1 Index Properties

Atterberg limits tests were performed on all the mixtures of bentonite and Bangkok clay, and the liquid limit (LL), plastic limit (PL) and plasticity index (PI) were determined as presented in Table 3.The results obtained from the Atterberg tests indicate that adding a proportion of Bangkok clay to bentonite has log-proportional effects on the LL and PL as shown in Figure 4. A similar effect can also be seen on the optimum moisture content (OMC) obtained in the compaction tests.

The LL of the mixture clays decreased over a wide range when the Bangkok clay content (BKK) increased, leading also to the decrease of the PL, PI, and OMC values. Louafi and Bahar (2012) reported on bentonite-sand mixtures that the reductions of the above properties are related to the decrease in the content of fine-grained soil that contributes to the plasticity. In contrast to earlier studies, Bangkok clay has the particle sizes apparently smaller than that of the bentonite (Figure 2) but it does not contribute to plasticity as much as the bentonite, as discussed earlier. Sabat (2012) found on lime stabilised expansive soil that increasing a lime content led to a decrease in the LL and PI and an increase in the PL and OMC. Compared to such behaviour, adding non-swelling clays seems to have simpler effect of bringing the plasticity log-linearly towards that of the added clay upon 100% replacement.

The reduction of the LL and PI against BKK is greater than those of PL and OMC. The result indicates that the plasticity and liquid limit are quite sensitive to the swelling clay content. This fact has been found in many types of clay. For example, Mitchell and Soga (2005) reported that the variation of LL for different clay mineral groups is greater than the variation of the PL. Figure 4 also indicates that the OMC-line is lower than the PL-line. The log-linearity observed in these relationships means that the greatest change of the LL value is observed when a first 20% dose of Bangkok clay is introduced to the pure bentonite. The decreases of the LL, PI and OMC became gradually modest as the BKK becomes higher. The implication of these reductions in the plasticity properties of a swelling clay added with a non-swelling clay is that the swelling clay becomes relatively friable and workable with a modest replacement.

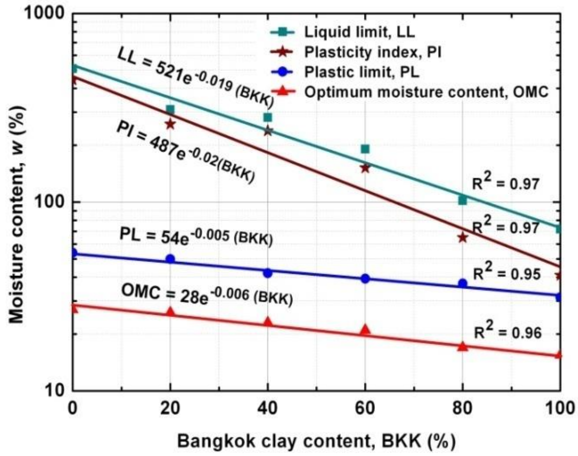


Figure 4 Effect of Bangkok clay content (BKK) on LL, PI, PL, and OMC of the bentonite-Bangkok clay mixtures

3.2 Compaction Behaviour and CBR

3.2.1 Compaction

Figure 5 presents compaction curves for varying BKK in the mixture clays. The maximum dry density (MDD) increases and the optimum moisture content (OMC) decreases monotonically as BKK increases. This is probably due to the fact that the non-swelling clay (Bangkok clay) requires less water for inter-particle lubrication than the swelling clay (bentonite). The zero air-void curves of the bentonite and Bangkok clay were plotted in the same diagram (Figure 5). These two lines are the envelopes for the zero air-void curves of all the mixture clays. It is noted that the compaction curve of the pure bentonite is much flatter than that of the Bangkok clay. This is because the bentonite has a very high plasticity index of 455%. During compaction bentonite needs much water content between each compaction steps than that of the Bangkok clay in order to attain a significant change of state. Figure 6 show a relationship between MDD and OMC obtained from the above compaction curves. The relationship has presented as a linearly in a relative wide range.

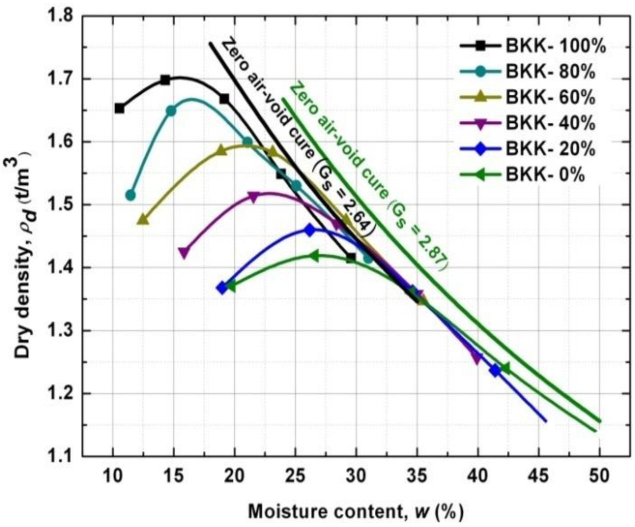


Figure 5 Effect of Bangkok clay content on compaction behaviour of the bentonite-Bangkok clay mixtures

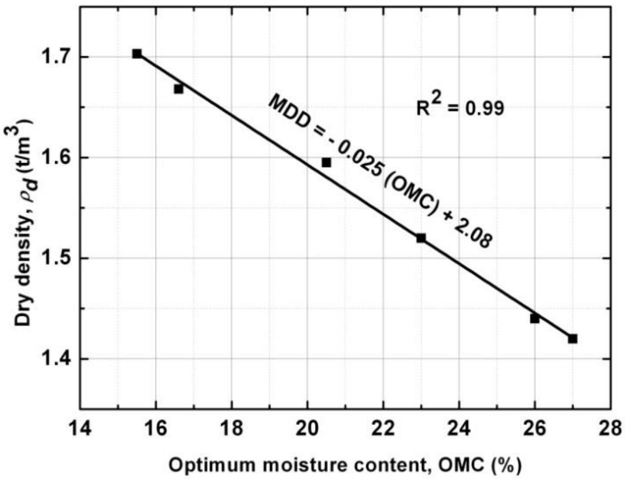


Figure 6 Relationship between OMC & MDD of bentonite-Bangkok clay mixtures

The relationships between MDD and OMC versus PI in this study are shown graphically in Figure 7(a) and (b), respectively. Theses relationships can be simplified as the following equations:

$$MDD = -0.0007PI + 1.7 \quad [t/m^3] \tag{2}$$

$$OMC = 0.03PI + 15.5 \quad [\%] \tag{3}$$

These relationships show that there is an increase in the MDD and decrease in the OMC while the PI decreases. In all the mixture clays, the highest MDD and the lowest OMC values were obtained at the lowest PI. This means that the highest MDD and the lowest OMC were obtained when the swelling clay (bentonite) is fully replaced by the non-swelling clay (Bangkok clay).

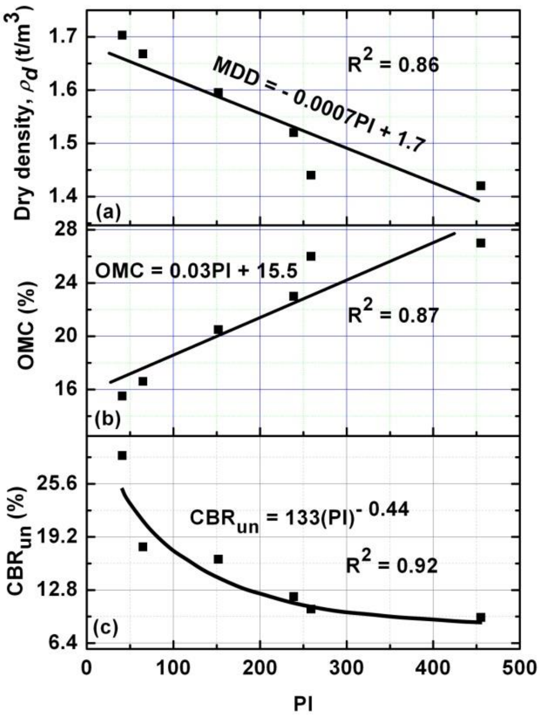


Figure 7 Relationship between MDD, OMC, and CBR_{un} versus PI of bentonite-Bangkok clay mixtures

3.2.2 California Bearing Ratio (CBR)

The results of the CBR tests on soaked and unsoaked conditions are presented in Table 4. It can be seen that the CBR value increased under both soaked and unsoaked conditions as the BKK increased. In unsoaked condition the CBR values of the mixture clays increased by 10.5, 26.3, 73.7, 89.5, and 205.3% compared to the CBR values of the pure bentonite, respectively. After being soaked, the CBR values for all the mixture proportions were very small, at less than 2.1% (Table 4). The effect of soaking on the CBR may be qualified by the CBR reduction ratio due to soaking, R;

$$R(\%) = \frac{CBR_{un} - CBR_s}{CBR_{un}} \times 100 \tag{4}$$

Where CBR_{un} = CBR under the unsoaked condition and CBR_s = CBR under the soaked condition.

Table 4 Summary of CBR values measured under soaked (65 days) and unsoaked of bentonite-Bangkok clay mixtures

Bangkok clay content (%)	0	20	40	60	80	100
CBR_{un} (%)	9.5	10.5	12.0	16.5	18.0	29.0
CBR_s (%)	0.50	0.65	0.75	0.9	1.1	2.1
R (%)	94.7	93.8	93.8	94.5	93.9	92.8

Razouki and Azawi (2003) on gypsiferous subgrade soil, Gurah and Razzaq (2009) on lime treated clay soil and Karthik et al. (2014) on soft fine-grained red soils stabilise by using fly ash have demonstrated that significant reductions of CBR were observed after soaking the samples and that the CBR decreased with increasing soaking period. This is because the structure of the clay sample became loosened after being soaked as evidenced by observing from swelling test results of each sample such as the increased vertical swelling strain due to increase soaking period (Figure 8). During soaking, the clay sample absorbed more moisture, which led the sample to swell and then become soft, and as a result the penetration stress became smaller and the CBR value decreased.

The changes of the vertical swelling strains of the compacted bentonite-Bangkok clay mixtures in the CBR mould during soaking are shown in Figure 8. It is observed that the swelling strain decreased significantly with increases in the BKK. For each 20% increment of the BKK from 0% to 100%, the effect on the vertical swelling was diminished gradually. The rate of the vertical swelling became smaller and almost reached a stable stage within 65 days when the BKK was more than 60%. The sample with less than 40% BKK continued to swell after 65 days. This may be due to the high swelling potential of bentonite coupled with a smaller permeability which resulted in slower water infiltration into the sample, requiring more time to reach a stable stage. As with plasticity, a modest addition of non-swelling clay has a significant effect of reducing the swelling potential as well as time to reach a stable state.

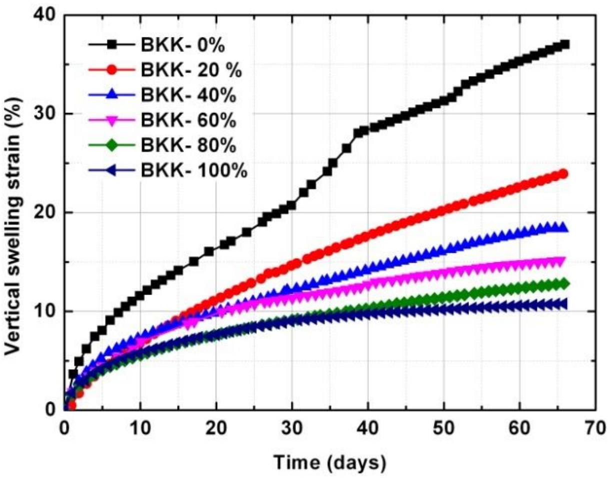


Figure 8 Vertical swelling of bentonite-Bangkok clay mixtures under a surcharge of 2.5 kPa during 65 days of soaking

Correlations between CBR values and soil index properties based on regression analysis are frequently used in many studies (Bello, 2012; Talukdar, 2014). From this study's results, the CBR_{un} had following relationships with PI:

$$CBR_{un} = 133PI^{-0.44} \quad [\%] \qquad (5)$$

In Figure 7(c), the plot of the above curves are shown. The PI decreased with an increase of the BKK in the mixture clays. When the PI of clay decreases, the OMC of clay decreases and the MDD increases, as confirmed earlier. Therefore, the strength increases and the CBR value increases (Figures 7). It is also comparable to the results from Nayak and Christensen (1971), Aghamelu et al. (2011), and Rani and Suresh (2013) on expansive soils, Naeini and Moayed (2009) on soft clay-bentonite mixtures and Talukdar (2014) on silts at multiple different sites. These authors stated that the CBR value decreased with an increase in the PI and the OMC of clay, while increasing with the increase in the MDD. In this study, the PI obtained from the mixture clays varies in a wide range of 41% to 455% (Figure 7). Due to this variation, a significant increase of the CBR values were obtained at the PI less than 150 which corresponding to the BKK higher than 60% in the mixture clays.

The correlations obtained from this study (Eqs. 3 and5) are tested against the data for other soil types including natural expansive clays obtained by previous researchers as shown in Table 5. Errors in predicted values against observed values are presented in the same table. The errors in the predicted values of OMC and CRB based on PI compare to the observed values in published studies are within the range of -4.5% to +3.9% and -10.6% to +7.5%, respectively, as presented in the Table 5. This is acceptable accuracy in most preliminary design work, particularly given the wide range of the soil types considered here, including expansive clays and those mixed with non-expansive clays.

Table 5 Comparison between observed and predicted values of OMC and CBR by using previous researcher's data on various expansive soils

Name of authors	Observed values		Predicted values	Errors (%)
			(Eq. 3)	
Talukdar, 2014	OMC (%) =	PI =	OMC (%) =	
(Nagaon soils,	15.1	7.9	15.7	+3.9
India)	15.2	7.5	15.7	+3.2
	15.8	8.4	15.7	-0.6
Nayak and	16	38	16.6	+3.6
Christensen, 1971	17	58	17.2	+1.1
(Expansive soils)				
Haricharan et al.,	17	24	16.2	-4.5
2013 (Black cotton				
soil, India)				
			(Eq. 5)	
Aghamelu et al.,	CBR (%) =	PI=	CBR (%) =	
2011 (Expansive	31	29	30.4	-1.9
clays induced	35	27	31.3	-10.6
shale)	36	19	36.5	+1.4
	41	13	43.0	+4.8
Ogundalu et al.,	24	42	25.8	+7.5
2013 (Expansive				
clay soils)				

3.3 Compression Behaviour

After reconstituting samples by applying the maximum vertical stress of 30 kPa, the equilibrium moisture contents and void ratios at the end of the reconstituting process were obtained, as presented in Table 6. They are considered to be the initial moisture contents (w_i) and void ratios (e_i) in the subsequent consolidation in the oedometer.

Table 6 Compressibility of the bentonite-Bangkok clay mixtures

Bangkok clay content (%)	0	20	40	60	80	100
Initial water content, w_i (%)	372	267	246	189	88	60
Initial void ratio (e_i)	11.65	9.74	6.87	4.31	3.80	1.55
Compression index (C_c)	6.2	5.0	3.4	2.1	1.7	0.6
Swelling index (C_s)	1.66	0.99	0.77	0.33	0.21	0.12

The relationships between the void ratio (e) versus the vertical effective stress (e-log σ') in one-dimensional compression were obtained as shown in Figure 9. It can be observed that the void ratio was smaller at a given stress level for larger BKK.

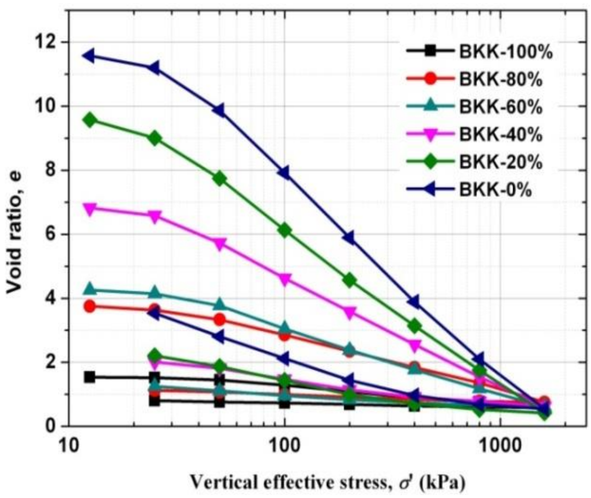


Figure 9 Compression curves of the bentonite-Bangkok clay mixtures

According to Sreedharan and Puvvadi (2013), the compressibility of any clay with a given pore fluid is generally controlled by the net repulsive pressure associated with the development of a diffuse double layer around the clay particles. With a decrease in bentonite and hence an increase in the BKK, the repulsive pressure decreases and the clay mixtures reach equilibrium with the applied effective pressure at lower void ratios. The relationships between the vertical coefficient of consolidation (c_v) and the log of vertical effective stress (c_v-log σ') of the clay mixture with different BKK were obtained as presented in Figure 10. The values for c_v were determined by the square root time method.

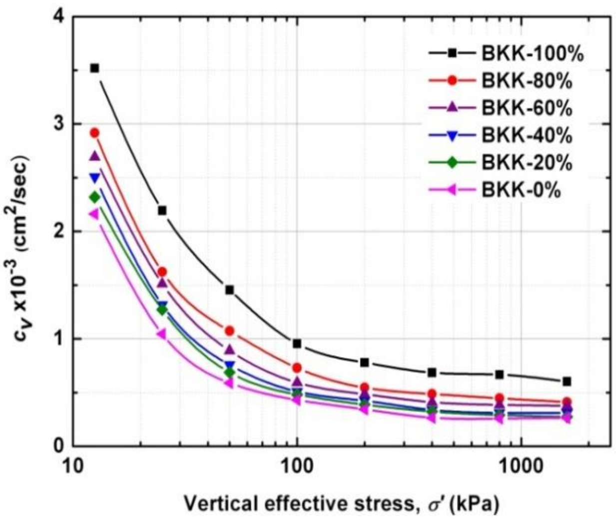


Figure 10 Vertical coefficient of consolidation versus vertical effective stress of the bentonite-Bangkok clay mixtures

The results indicate that the c_v value decreases significantly with an increase in both the vertical effective stress and the BKK. In contrast to these results, Rabbee and Rafizul (2012) reported on reconstituted organic soil that the c_v value increased with an increase in both the organic content and the effective stress. But similar behaviour to this study was also observed for higher effective stress levels in the same study, with c_v converging to a constant value. The present study, applying the effective stress of 12.5 kPa to 1600 kPa, c_v decreased significantly for all the mixture clays and became almost constant at an effective stress of around 400 kPa. At this effective stress the correlation between c_v and PI was obtained as shown in Figure 11 and expressed as

$$c_v = 0.0025\text{PI}^{-0.364} \quad [\text{cm}^2/\text{sec}] \tag{6}$$

In Figure 11, it is clear that for all the mixture proportion at the same effective stress, c_v decreased significantly with an increase in PI.

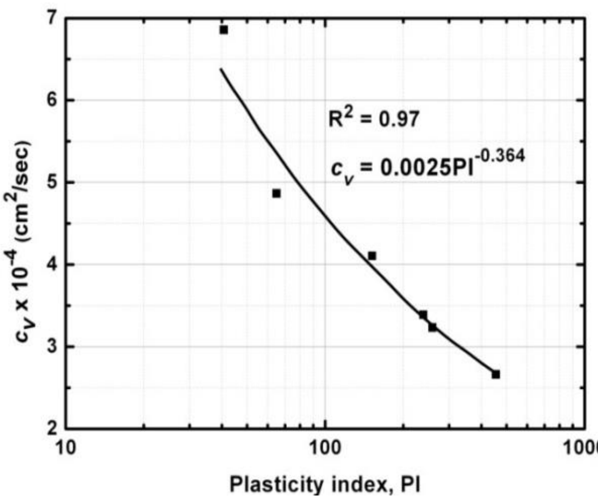


Figure 11 Correlation between c_v and PI of bentonite-Bangkok clay mixtures

The correlation between the compression index, C_c, and swelling index, C_s, and that between C_c and LL obtained from all the mixture conditions were presented in Figure 12(a) and (b), respectively. From the figure, it can be perceived that when C_s and LL increase, C_c also increases. The swelling index is usually appreciably smaller in magnitude than the compression index (C_s/C_c = 0.1-0.2; Das, 2006). Linear correlations were obtained between the above properties as:

$$C_c = -1.284\,(C_s)^2 + 5.76\,C_s \tag{7}$$

$$C_c = 0.013\text{LL} + 0.05 \tag{8}$$

Comparing the predicted values (Eq.8) to the observed values of C_c by using data of earlier investigators, the errors obtained are within the range of -14% to +9.2% as presented in the Table 7. From the results, it can be observed that there are slightly different in the prediction value of C_c using the equation obtained in this study (Eq.8). However, the correlation in this study (Eq.8) should be applicable to other soil types in term of preliminary prediction.

Table 7 Comparison between observed and predicted values of C_c by using previous researchers' data

	Observed values		**Predicted values**	**Errors (%)**
			(Eq. 8)	
	C_c =	LL=	C_c =	
Widodo and Ibrahim, 2012 (Pontianak soft clay)	0.279	17	0.269	-3.2
	0.349	25	0.369	+5.9
	0.511	39	0.558	+9.2
	0.663	48	0.678	+2.2
	0.738	49	0.683	-7.4
	0.866	53	0.744	-14

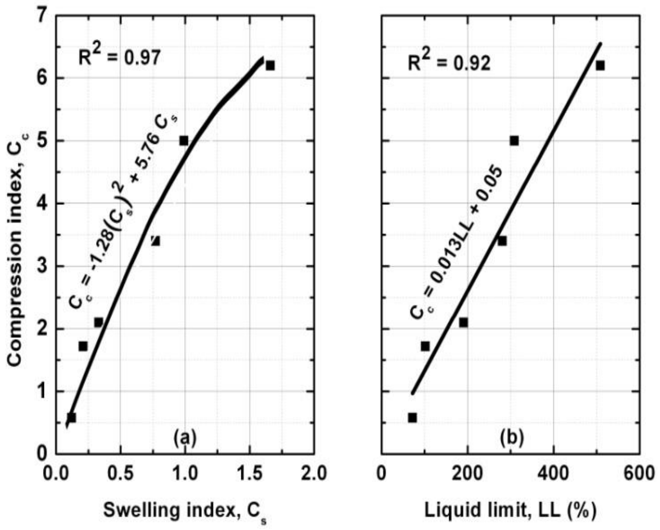


Figure 12 Correlations between C_c, C_s and LL of bentonite-Bangkok clay mixtures

Eq.8 is also compared to some equations proposed by previous researchers for a variety of fined-grained soils. They are summarised in Table 8.

Table 8 Methods prediction compression index (C_c)

Name authors	Equations	Soil types
This study	0.013LL + 0.05	Bentonite-Bangkok clay mixtures
Yoon et al. (2004)	0.012(LL+16.4)	marine clays: (Coast south Korea)
	0.011(LL-6.36)	Coast east Korea
	0.01(LL-10.9)	Coast west Korea
Hough (1957)	0.0046(LL-9)	Brazilian clays
Terzaghi and Peck (1967)	0.009(LL-10)	Clays
Skempton, 1944	0.007 (LL-7)	Remoulded clays
Nagaraj and Murty (1985)	0.0463(LL/100)G_s	All inorganic clays
Kahdaar and Ameri (2010)	0.00556LL	Silty clay

By inputting the measured index property values of the bentonite-Bangkok clay mixtures to each proposed equations in Table 8, the C_c values are calculated as shown in Figure 13. The C_c values obtained from the laboratory results are all larger than the expected from the LL and the conventional equations. The two end point data (pure Bangkok clay and pure bentonite) could not be captured by the existing equations and it affected the prediction for the mixed states. The C_c values predicted from all existing relationships are all smaller than those observed from the laboratory. This is because the materials used in this study are artificial expansive soils which have high plasticity index. The properties might be quite different from other clays in literatures. This indicates that to measure the compression of swelling soils it requires carefully observation from laboratory test.

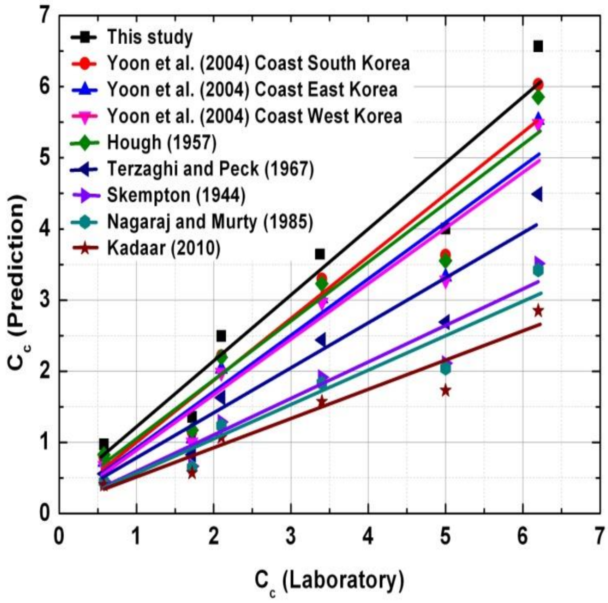


Figure 13 Actual compression index (C_c) versus predicted compression index

3.4 Strength Characteristics

Unconfined compression tests (UC) were performed immediately after removing the samples from the consolidometer. The water contents at this stage are presented in Table 6. From the UC test results, stress-strain curves were obtained as shown in Figure 14 with the following observations. As the BKK increased, the unconfined compressive strength (q_u) clearly increased. Clear failure points after which strain-softening occurred were observed in the samples with 80% and 100% BKK, with the q_u of 12.8kPa and 17.6 kPa at the axial stains of 5.4% and 4.8%, respectively. When the BKK in the clay mixtures was smaller than 80%, there was no clear peak strength and the behaviour was ductile.

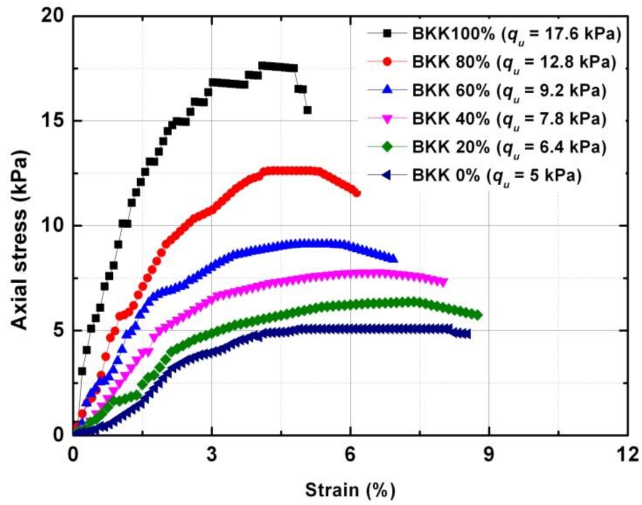


Figure 14 Effect of Bangkok clay content on unconfined compression strength of reconstituted bentonite-Bangkok clay mixtures

3.5 Shrinkage Behaviour

After air-drying specimens from the initial moisture contents set at their LLs until reaching stable states, the areal shrinkage strains (ASS) were observed by using an image processing technique as explained earlier. The measured ASSs are shown in Figure 15. The ASS of bentonite-Bangkok clay mixture decreased with an increase in the BKK. This is because the moisture content at the LL of the clay mixtures, set as the specimen's initial condition, decreased with increasing BKK. Similarly to this study, Mitchell and Soga (2005) and Puppala et al. (2013) mentioned that the greater the plasticity is, the greater shrinkage is expected.

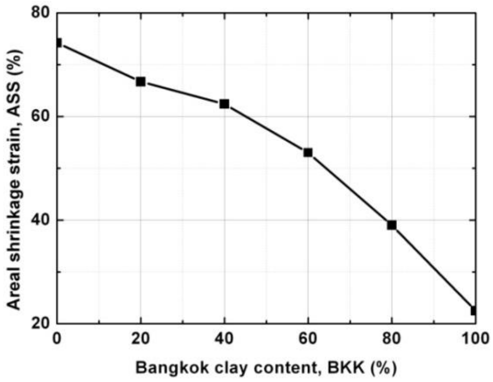


Figure 15 Effect of Bangkok clay content on areal shrinkage strain of the bentonite-Bangkok clay mixtures

The study by Puppala et al. (2007) on expansive clay mixed with two types of compost (biosolids compost, BS and dairy manure composts, DMC) showed that the linear shrinkage strain, in this study called areal shrinkage strain (ASS), decreased with increasing amount of BS and DMC. These authors observed that, with higher moisture contents at initial stages, larger shrinkage strains upon drying were obtained. The decrease of ASS for each 20% increment of BKK was larger for smaller BKK (Figure 15), indicating that an initial modest dose of a non-expansive clay mixed into an expansive clay has disproportionally large effects in reducing the shrinkage potential.

This study measured the residual moisture content ($w_{a.d}$) for clay mixture with different clay constituent proportions after room-air drying, and correlations between $w_{a.d}$ and the ASS and that between $w_{a.d}$ and LL are presented in Figure 16(a) and (b), respectively.

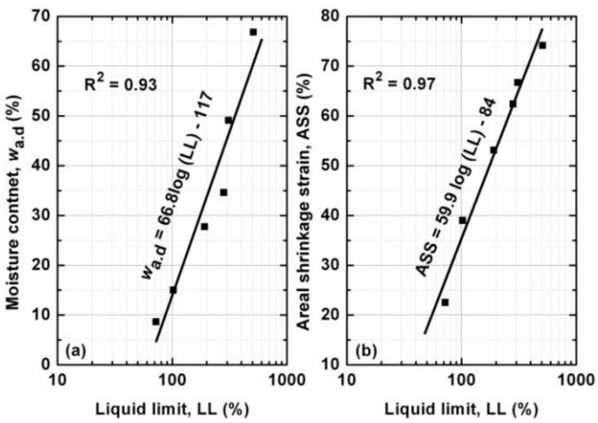


Figure 16 Relationship between (a) LL versus $w_{a.d}$ and (b) LL versus areal shrinkage strain after room-air dry in bentonite-Bangkok clay mixtures

The correlations are expressed by the following equations:

$$w_{a.d}\ (\%) = 66.8 \log (LL) - 117 \tag{9}$$

It is clear that with lower LL, lower $w_{a.d}$ and ASS were obtained. The decrease of the above properties is directly related to the decrease in the amount of expansive clay content.

4. CONCLUSIONS

This paper presents the results of a laboratory investigation on the influence of non-swelling clay on physical and mechanical properties of swelling clay, when they are mixed together. Specimens were made by mixing expansive bentonite and non-expansive Bangkok clay. The findings from the study can be summarised as follows:

1. The liquid limit (LL), plastic limit (PL), and optimum moisture content (OMC) significantly decreased when the Bangkok clay content (BKK) was increased in the mixture, and those properties exhibit in a semi-log linearity against the BKK. A greatest change of the index properties such as LL value was observed when a first 20% dose of Bangkok clay was introduced to the pure bentonite.
2. The strength, maximum dry density (MDD), and CBR values increased with increasing BKK. The strength obtained for the reconstituted samples of the clay mixture with the BKK less than 60% were very low (q_u less than 9.2kPa against a preconsolidation pressure of 30kPa), which would fall short of any engineering requirement. The best fit trend lines of OMC and CBR versus plasticity index (PI) have been developed. The errors in the predicted values and observed values of OMC and CBR using data of the previous studies on natural clays are within the range of -4.5% to +3.9% and -10.6% to +7.5%, respectively. This demonstrates that the correlations obtained in this study (Eqs.3 and5) are applicable to other soil types.
3. The vertical swelling was diminished gradually for each 20% increment of the BKK from 0% to 100%. The sample with less than 40% BKK continued to swell after 65 days of soaking. This is because the higher LL clays had higher swelling potential and lower permeability, hence requiring longer time to reach a stable state.
4. The compression index (C_c), the vertical coefficient of consolidation (c_v) and the swelling index (C_s) were significantly correlated to the LL and other index properties, which are in turn dependent on the swelling and non-welling clays content. An empirical relationship for compression index, C_c as function of LL established from this study was tested to predict C_c from existing studies on other soil types. The errors in the predicted values were within the range of -14% to +9.2%, which is still acceptable in preliminary design phase.
5. The areal shrinkage strains were strongly affected by non-swelling clay content (BKK), decreasing with increasing BKK. The initial water contents and the amount of swelling clay content are the main factors controlling the areal shrinking strain value.
6. The clay mixtures with smaller BKK, with their higher plasticity, experienced large volume changes during swelling and shrinkage. This confirms that such a feature, well established for naturally occurring clays, also applies to a mixture of two distinctly different clays.
7. This study found that many properties of an expansive soil undergo favourable changes when mixed with a modest dose (20-40%) of non-expansive clays. When locally occurring expansive clay ground is to be improved by mixing with transported non-expansive geomaterials, the findings here are useful in exploring an optimum proportions at preliminary design stages.

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