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Characteristics of expansive soils improved with cement and fly ash in Northern Thailand

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Abstract. This paper studies the swelling and strength characteristics of unimproved and improved expansive soils in terms of the swell potential, swelling pressure, rate of secondary swelling, unconfined compressive strength and California bearing ratio (CBR). The admixtures used in this study are locally available cement and fly ash. The soils used in this study were taken from the Mae Moh power plant, Lampang Province, in northern Thailand. A conventional consolidation test apparatus was used to determine the swelling of the soil specimen. The optimum admixture contents are determined to efficiently reduce the swelling of unimproved soil. The rate of secondary swelling for unimproved soil is within the range of highly plastic montmorillonite clay, whereas the specimens improved with optimum admixture contents can be classified as non-swelling kaolinite. A soil type affects the swelling pressure. Expansive soil improvement with fly ash alone can reduce swelling percentage but cannot enhance the unconfined compressive strength and CBR. The strength and swelling characteristics can be predicted well by the swelling percentage in this study.

Keywords: expansive soil, consolidation, degree of expansion, soil improvement

1. Introduction

Expansive soils are found in arid or semiarid regions and in temperate climate zones. These soils exhibit high plasticity, high swell potential, low strength and durability. Consequently, these soils are poorly suited for construction and are considered problematic (Seed *et al*. 1962, Alawaji 1999, Cokca 2001, Erguler and Ulusay 2003). Principally, when the moisture content increases, the expansive soils exhibit high volumetric expansion, while when the moisture content decreases, the soils shrink due to presence of montmorillonite clay, which has well-shrink potential (Chen 1988), thus giving rise to ground movement. This movement can cause severe structural damage, foundation cracks, floor slab cracks and roadway distress, as reported in many countries (Daniel and Wu 1993, Alawaji 1999). In the past, if such soils were found in a construction area, the Econstruction site may have been changed or the soils replaced by high-quality materials. Today, populations are increasing, construction sites are limited and the quality of construction material is

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decreasing. Therefore, the expansive soils are increasingly used as subgrade or fill materials in civil engineering projects. Yong *et al*. (1986) utilized expansive soils as back fill materials. Daniel and Wu (1993) and Alawaji (1999) reported that expansive soils have been used as soil barriers, landfill liners, and vertical barrier walls.

2. Swell potential classification

Seed *et al*. (1962) classified the swell potential of expansive soils based on odometer swell potential values. The remolded specimens were compacted at their Standard Proctor MDD (maximum dry density) and OMC (optimum moisture content) values and inundated under a pressure of 7 kPa. Swell potential and swelling pressure depend on various factors, including soil type, clay minerals found in the soil, initial dry density, void ratio, overburden pressure, natural moisture content, nature of the pore fluid, exchangeable cations, and the effect of wetting and drying (Chen 1988, Nelson and Miller 1992, Day 1994, Al-Homoud *et al*. 1995). Sridharan and Gurtug (2004) proposed a linear relationship between the swell potential and the swelling pressure of compacted clays.

3. Soil improvement method

To mitigate these swelling problems, soil improvement methods are introduced. Cement is an admixture that is widely used in the construction of roads, airports, embankments, or canal linings by mixing with clay subgrades to improve strength, swelling characteristics, and bearing capacity. The effects of cement stabilization on clay soils have been investigated by many researchers (Porbaha *et al*. 1998, Miura *et al*. 2001, Jelisic and Leppanen 2003, Rotta *et al*. 2003, Lorenzo and Bergado 2004, 2006, Voottipruex *et al*. 2011). Fly ash has been shown to effectively improve soft inorganic soils (Bin-Shafique *et al*. 2004, Prabakar *et al*. 2004, Trzebiatowski *et al*. 2005, Tastan *et al*. 2011). Fiber inclusions cause significant modification and improvement in the engineering behavior of soils. A number of research studies on fiber-reinforced soils have recently been performed, unconfined compression tests CBR tests and flexural strength tests (Maher and Ho 1994, Consoli *et al*. 2002, Santoni *et al*. 2001, Kumar *et al*. 2005, Sukontasukkul and Jamsawang 2012).

4. Scope of present study

There are plans to construct a road embankment and parking area at the Mae Moe power plant, located in Lampang province, Thailand. The construction materials available for this project are the problematic expansive soils found near the plant. Because of the insufficient improvement of the expansive soils from the addition of admixtures, this research aims to investigate the swelling and strength characteristics of unimproved and improved expansive soils in terms of swell potential, swelling pressure, rate of secondary swelling, unconfined compressive strength and California bearing ratio (CBR). Fiber is difficult to obtain, so the admixtures used in this study are locally available cement and fly ash. The optimum amount of admixtures is determined to efficiently reduce the swell potential. The soils used in this study were taken from the Mae Moh power plant, Lampang Province in the north of Thailand as shown in Fig. 1. A conventional

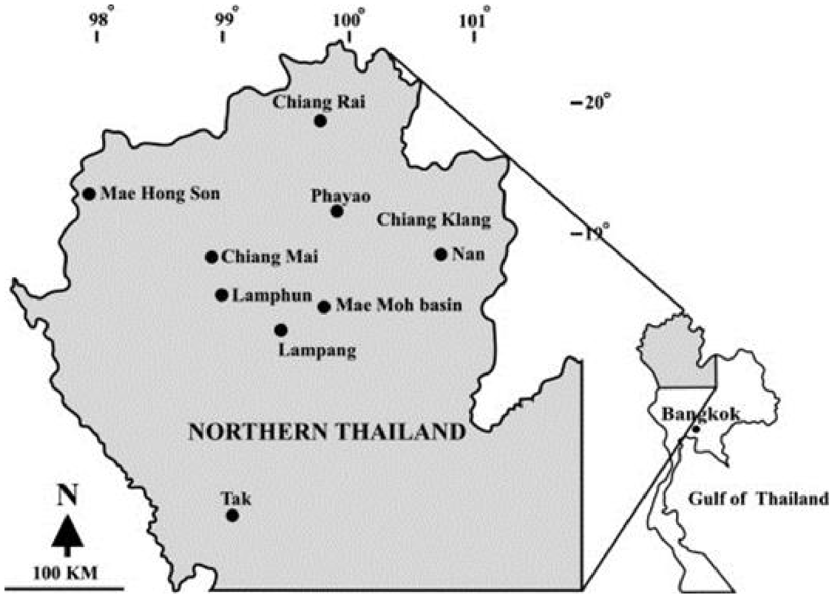


Fig. 1 Location of Mae Moe, Lampang province, Thailand

consolidation test apparatus was used to determine the swelling of the soil specimen in accordance with ASTM D4546-96. A study was made of the swelling index that was used to estimate engineering properties such as the unconfined compressive strength, the secondary swelling index, the swelling pressure and the CBR.

5. Materials and method of mixture preparation

The physical properties of unimproved soil are presented in Table 1. The soil was classified as CH due to the large amount of fine-grained soil (91.2%); the amount of gravel and sand in the soil was equal to 8.8%. The liquid limit was 72%, and the plastic index was 40%. To study the characteristics of expansive soil, the laboratory tests performed on samples included a one-dimensional swelling test, an unconfined compressive strength test and a California bearing ratio (CBR) test. All tests were conducted using the following procedures suggested by ASTM standards.

The standard Proctor test was performed to obtain the maximum dry unit weight, $\gamma_{d(max)}$, and optimum moisture content (OMC). The test employs a mold with a volume of 944 cm^3, an internal diameter of 10 cm and a height of 11.68 cm in which the soil is compacted in three layers. Each layer is given 25 blows with a metal hammer weighing 2.5 kg and falling 30.5 cm (ASTM D 698-12).

The admixtures are locally available and include cement and fly ash, which is a by- product material from the power plant, properties and classifications of fly ash and cement are presented in Table 2. The mixing ratio of the cement in this study is 1%, 3%, 5% and 7% by weight of dry soil, while the mixing ratio of the fly ash is 5%, 10%, and 20% by weight of dry soil. A combination of

Table 1 Physical properties of original soil sample

Property	Value
Gravel (80 – 4.75 mm), %	3.2
Sand (4.75 – 0.075 mm), %	5.6
Silt & Clay (%)	91.2
Classification	CH
Specific gravity	2.66
Liquid limit (%)	72
Plastic limit (%)	32
Plastic index (%)	40
Maximum dry unit weight from stand proctor test (kN/m^3)	14.9
Optimum moisture content (%)	26.2

Table 2 Properties and classifications of fly ash and cement

Parameter	Fly ash	Cement
SiO_2 (%)	29.15	20.61
Al_2O_3 (%)	15.66	5.03
Fe_2O_3 (%)	15.97	3.03
SO_3 (%)	4.98	2.70
CaO (%)	23.05	64.89
MgO (%)	2.15	1.43
Specific gravity	2.65	3.15
Loss of ignition (%)	2.11	1.23
Classification	Class C	Ordinary Portland cement
		Type1-Grade 53

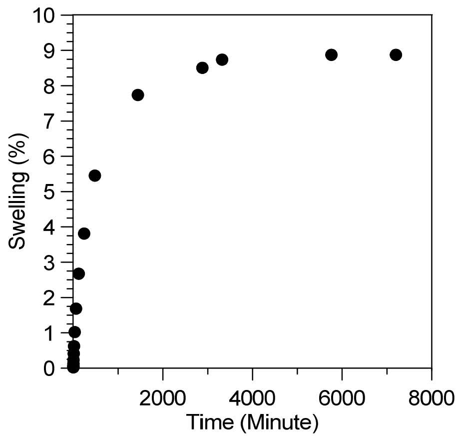
cement with fly ash could contribute strongly to the development of the strength and durability of the improved expansive soil. Cement was used in soil specimens as necessary for energy conservation in, combinations of 1% cement and 5%, 10%, or 20% fly ash.

To quantify the swell potential, swelling pressure and secondary compression index, the swelling tests were performed in the conventional consolidation test apparatus. The specimen preparation of both improved and unimproved soils was controlled by a maximum dry unit weight of 14.9 kN/m^3 and an optimum moisture content of 26.2% from the standard Proctor test. Each specimen was pressed carefully in a standard fixed-ring consolidometer made from stainless steel with a 55 mm inside diameter and a height of 19 mm. All specimens were inundated under a pressure of 7 kPa to measure the swell potential. Unconfined compressive strength tests (ASTM D 2166-00) were conducted and the CBR (ASTM D 1883-07) of the specimens was determined. The specimens were controlled by the same maximum dry unit weight and optimum moisture content. For unconfined compressive strength tests, the specimens with a 50 mm diameter and 100 mm height were formed in the mold by slowly being compressed with a hydraulic jack. For the CBR tests, the number of blows used was 56. The specimens were cured for 28 days before the tests.

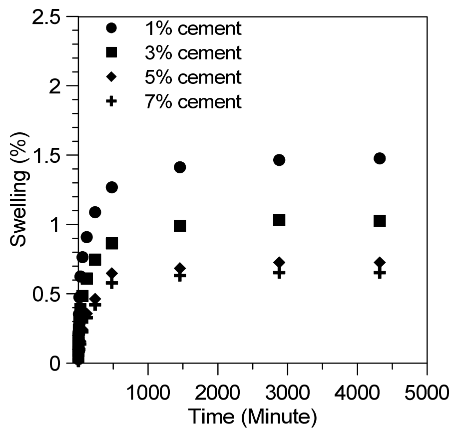
6. Consolidation test results

6.1 Swelling versus time curve

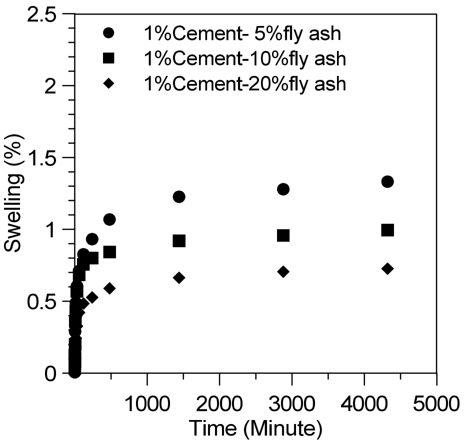
Figs. 2(a) to (d) present the time and swelling for the unimproved and improved expansive soils with cement, 1% cement mixed with fly ash and fly ash. Swelling is defined as the ratio of the amount of swelling to the original thickness of the sample expressed as a percentage. It can be observed that the increase in the swelling percentage is quite rapid at the initial stage and that it gradually reaches the asymptotic level. It takes approximately 4000 minutes to reach near-equilibrium for unimproved expansive soils whereas all improved soil specimens take only



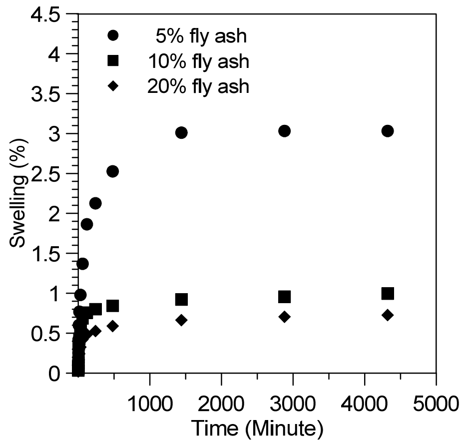
(a) Unimproved soil



(b) Improved soil with cement



(c) Improved by 1% cement and fly ash



(d) Improved by fly ash

Fig. 2 Relationship between time and swelling approximately 500 to 1000 minutes. The time is reduced due to the lower plasticity index (PI) of the improved soil specimens; the lower the plastic index, the less time it takes to reach near-equilibrium, the smaller is the time taken to reach near equilibrium (Sridharan and Gurtug 2004), as shown in Table 3. The plasticity index of the improved soil specimens indicates that the admixture improvement resulted in lower plasticity properties compared with the unimproved soils. As the amount of admixture increased, the liquid limit (LL) decreased, and an increase in the plastic limit (PL) was obtained; therefore, the plasticity index decreased. When the admixture was added to clay, a cation exchange reaction took place. This reaction decreased the double-layer thickness, resulting in an increase in the attraction forces, which led to better flocculation of the particles. The test results of Sridharan and Gurtug (2004) also showed that near-equilibrium was reached in less than 24 hours for kaolinite (PI = 7.1%) and in approximately 7 days for montmorillonite clay (PI = 58%), implying that the swelling behavior of unimproved soil in this study lies between kaolinite and montmorillonite clay whereas the improved soils behave like kaolinite.

6.2 Rate of swelling and maximum swelling

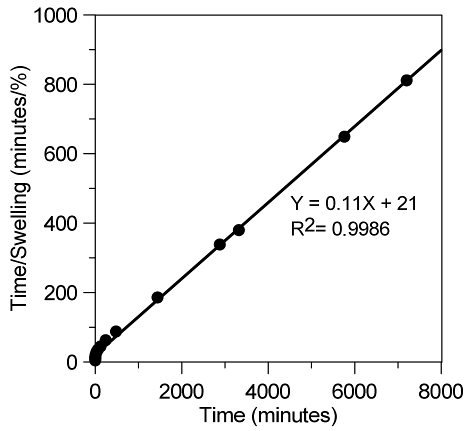
Basma and Tuncer (1991) defined the rate of swelling as the time required to reach 50% swelling (the time to half the maximum swelling). This definition was adopted from the consolidation theory for the determination of the rate of consolidation. However, it should be noted that the behaviors of swelling and consolidation are completely different. Daksanamurthy (1978) proposed a hyperbolic equation to predict the swelling of expansive soils as given in Eq. (1)

$$\frac{t}{S} = a + bt \tag{1}$$

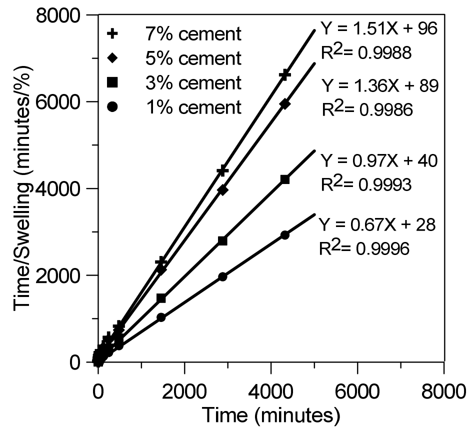
The plots of swelling, S, versus time, t, in Fig. 2 have been transformed into plots of t/S versus t in Fig. 3 showing the almost perfect linear relationship between time and time/swelling. The constants a and b are defined by the straight line. Herein, b is the slope of the swelling path. Moreover, the rate of swelling can be known by the value of the slope, b, which shows the flow of the swelling path. Therefore, b is defined as the coefficient of the swelling rate. A steeper slope is a sign that the rate of swelling is smaller. As shown in Table 3 that the swelling rate coefficient of the cement-improved soil increased with increasing cement content. However, the swelling rate coefficient for the expansive soil improved by 1% cement with fly ash and fly ash alone also increase compared with unimproved soil, exhibiting the lowest coefficient of the swelling rate of 0.11. Moreover, Table 3 presents the maximum swelling (S_{max}) for the unimproved and improved soils. The maximum swelling of the unimproved soil is found to be 8.8% classified as a high degree of expansion based on the classification of Seed *et al*. (1962).

The actual maximum swelling tabulated in Table 3 can be predicted using a hyperbolic equation, obtained from the asymptotic line of a hyperbola, and it can be calculated using $1/b$. (Dakshinamurthy 1978, Rao and Kodandaramaswamy 1980, Sridharan *et al*. 1*986*). Fig. 4 shows the relationship between actual maximum swelling and the predicted maximum swelling obtained from $1/b$. The studies show that the predicted maximum swelling is 1.02 times the actual maximum swelling.

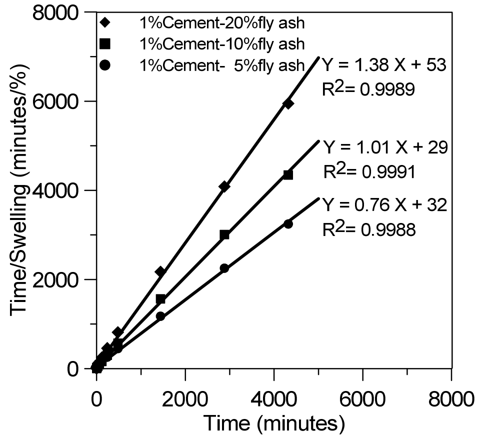
The relationship between the maximum swelling (S_{max}) and the plasticity index (PI) of unimproved and improved expansive soils from this study and studies by Seed *et al*. (1962), Chen (1988) and Sridharan and Gurtug (2004) are shown in Fig. 5. The correlation in this study



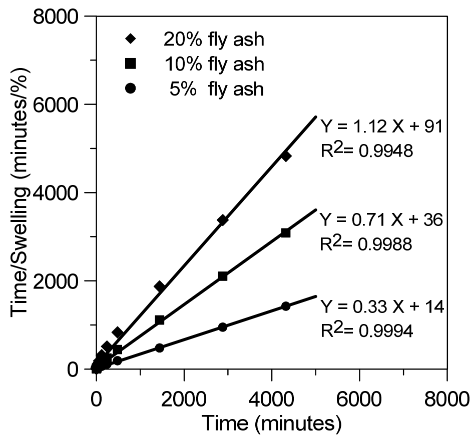
(a) Unimproved soil



(b) Improved soil with cement



(c) Improved by 1% cement and fly ash



(d) Improved by fly ash

Fig. 3 Relationship between time and time-swelling ratio

exhibits a unique exponential curve of $S_{max} = 0.0056e^{-0.123PI}$ with $R^2 = 0.8765$, corresponding to the relationship presented by Chen (1988) rather than Seed *et al.* (1962) and Sridharan and Gurtug (2004). However, the maximum swelling (S_{max}) decreased as the PI decreased, corresponding to previous studies.

In this study, the effect of the admixture content on maximum swelling is shown in Fig. 6. The swelling decreases rapidly when the cement content increases from 0% to 3% and slightly decreases when the cement content is higher than 3%. It can be considered that 3% cement is an optimum cement content that efficiently reduces the swelling of unimproved soil from 8.8% to 1.03% with swelling ratio of 8.5, as shown in Table 3. The swelling ratio is defined as the ratio of the swelling of unimproved soil to the swelling of improved soil. For cost effectiveness, the combination of 1% cement mixed with 8% fly ash and 14% fly ash alone are also optimum admixture contents providing the same swelling (1.03%) of the improved soils compared with

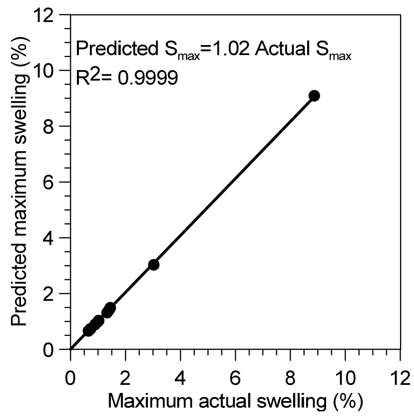


Fig. 4 Relationship between actual swelling and predicted swelling of unimproved and improved soils

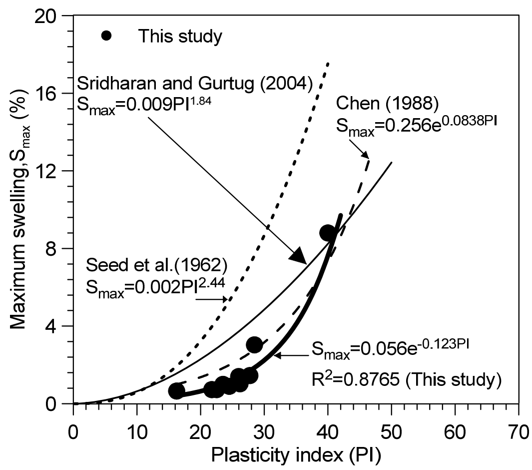


Fig. 5 Relationship between maximum swelling and plasticity index of unimproved and improved soils

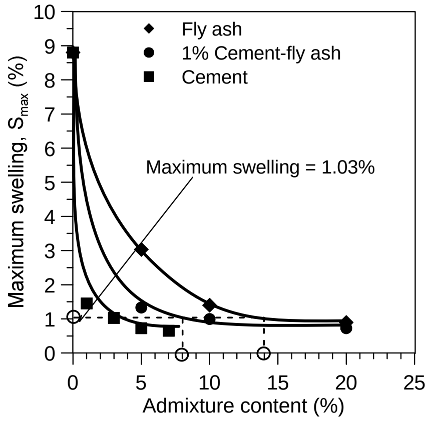


Fig. 6 Effect of admixture content on maximum swelling of unimproved and improved soils

Table 3 Properties of unimproved and improved soil

Soil type	Plasticity index (%)	Coefficient of swelling rate	Maximum swelling (%)	Rate of secondary swelling	Swelling pressure (kPa)	Swelling ratio
Unimproved soil	40.0	0.11	8.80	0.01224	160	
Improved soil						
1% cement	27.7	0.67	1.45	0.00176	200	6.1
3% cement	26.2	0.97	1.03	0.00142	140	8.5
5% cement	22.5	1.36	0.73	0.00076	90	12.1
7% cement	16.2	1.51	0.65	0.00077	80	13.5
1% cement-5% flyash	26.6	0.76	1.33	0.00299	130	6.6
1% cement-10% flyash	23.5	1.01	0.99	0.00209	100	8.9
1% cement-20% flyash	21.8	1.38	0.73	0.00120	80	12.1
5% flyash	28.5	0.33	3.03	0.00649	160	2.9
10% flyash	26.0	0.71	1.40	0.00245	80	6.3
20% flyash	24.5	1.12	0.89	0.00239	40	9.9

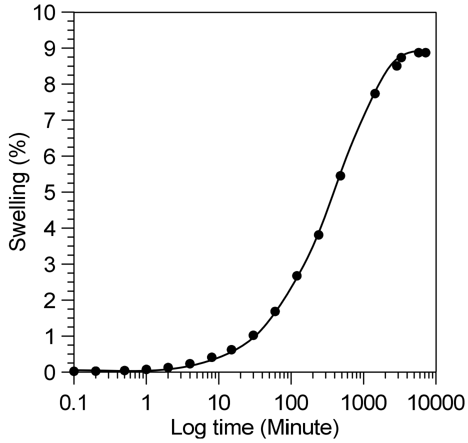
3% cement alone. In addition, the maximum swelling (1.03%) of the improved soil with the aforementioned optimum admixture contents can be classified as having a low degree of expansion based on classification of Seed *et al*. (1962).

6.3 Secondary swelling rate

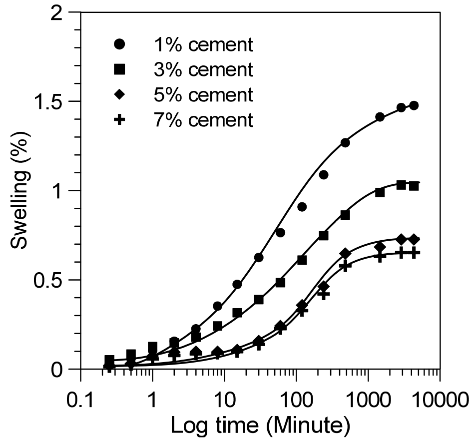
Fig. 7 plots swelling and the log of time. These curves are s-shaped, exhibiting initial primary and secondary swelling that is similar to conventional consolidation test results. The low swelling rate during the initial stage is attributed to the low unsaturated hydraulic conductivity of the samples. Once water mobility was initiated, the high water adsorptive forces on the clay particle surfaces were readily wetted, thereby resulting in a high rate of primary swelling. The gradual reduction in the swelling rate during the primary and secondary swelling is attributed to the increasing sample saturation due to water migration (Shahid 2006). The secondary swelling rate is similar to the rate of secondary compression (Lambe and Whitman 1979), which can be calculated according to the following formula

$$C_{\alpha s} = \frac{\Delta e}{\log \frac{t_2}{t_1}} \tag{2}$$

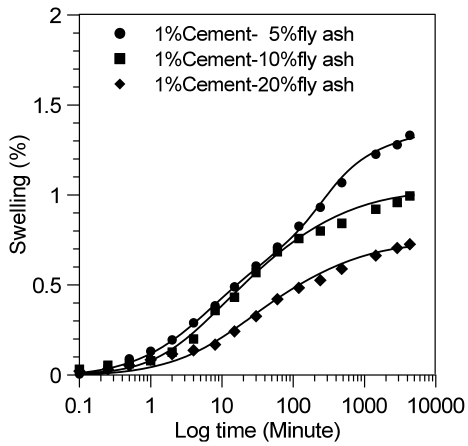
where $C_{\alpha s}$ is the secondary swelling rate, Δe is the change in void ratio and t_1 and t_2 are the time period. Table 3 shows a summary of the rates of secondary swelling, which is facilitated by long-term predictions of swelling for all soil specimens. The maximum rate of secondary swelling of unimproved soil is 0.01224. In this study, the secondary swelling rate of the cement-improved soil decreased from 0.00176 to 0.00077 as the cement content increased from 1% to 7%. When different amounts of fly ash were added to the specimen improved with 1% cement, the secondary



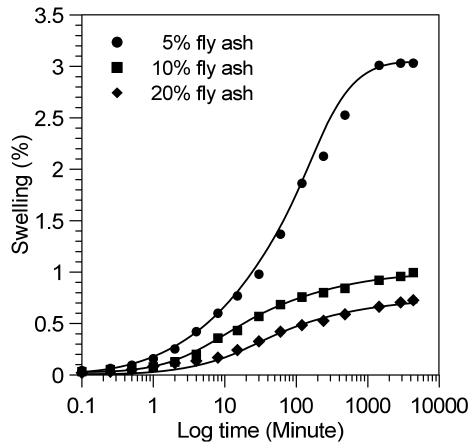
(a) Unimproved soil



(b) Improved soil with cement



(c) Improved by 1% cement and fly ash



(d) Improved by fly ash

Fig. 7 Log time and swelling

swelling rate decreased as fly ash content increased from 0.00299 to 0.00120, as shown in Table 3. Moreover, for the expansive soil improved with fly ash alone, the secondary swelling rate also decreased from 0.00649 to 0.00245 and slightly decreased to 0.00239 as the fly ash content increased from 5% to 10% to 20%.

Sridharan and Gurtug (2004) reported that the rate of secondary swelling is almost zero for non-swelling kaolinite. For the less-plastic soil (PI = 12.1%), the rate of secondary swelling ranged from 0.00124 to 0.00495, and it varied from 0.0123 to 0.0236 for highly plastic montmorillonite clay (PI = 58%). Fig. 8 presents the effect of the admixture content on the rate of secondary swelling together with the results of Sridharan and Gurtug (2004). It can be observed that the rate of secondary swelling for unimproved soil in this study is within the range of highly plastic montmorillonite clay. The specimens improved with 3% to 7% cement and with 1% cement-20% fly ash can be classified as non-swelling kaolinite. However, the specimen improved with fly ash

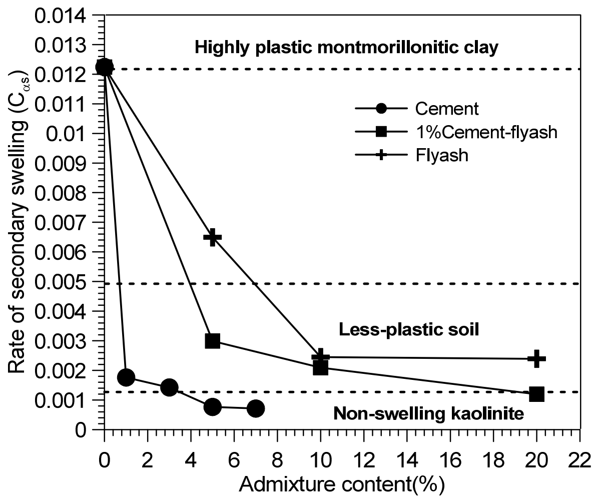


Fig. 8 Effect of admixture content on rate of secondary swelling of unimproved and improved soils

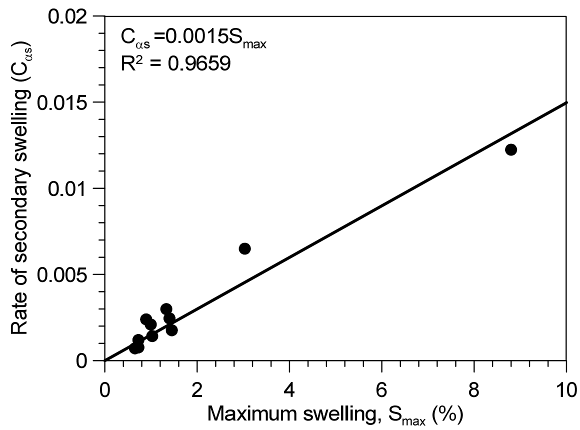


Fig. 9 Maximum swelling and secondary swelling rate of unimproved and improved soils

alone cannot be considered as non-swelling kaolinite. In Fig. 9, the empirical relationship of the rate of secondary swelling ($C_{\alpha s}$) with maximum swell ($S_{\max}$) can be expressed as follows

$$C_{\alpha s} = 0.0015\, S_{\max} \quad (R^2 = 0.9659) \tag{3}$$

6.4 Swelling pressure

The swelling pressures (SPs) of expansive soil specimens are shown in Table 3. The swelling pressure is defined as the pressure required to compress a specimen that has been soaked and completely swollen under seating pressure back to its original configuration (Sridharan *et al.* 1986). It can be observed that the swelling pressure increased as the maximum swelling increased. The

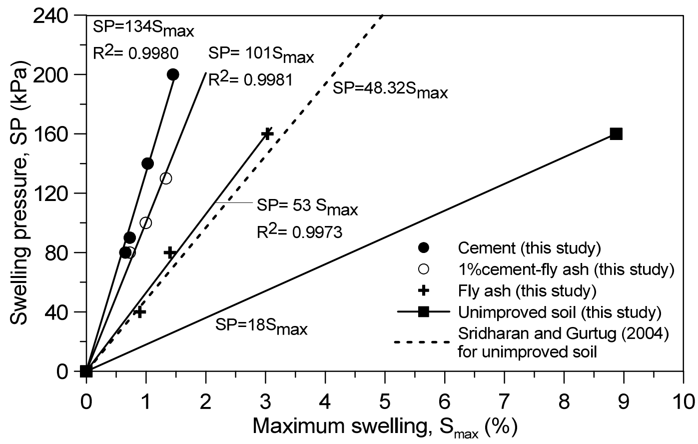


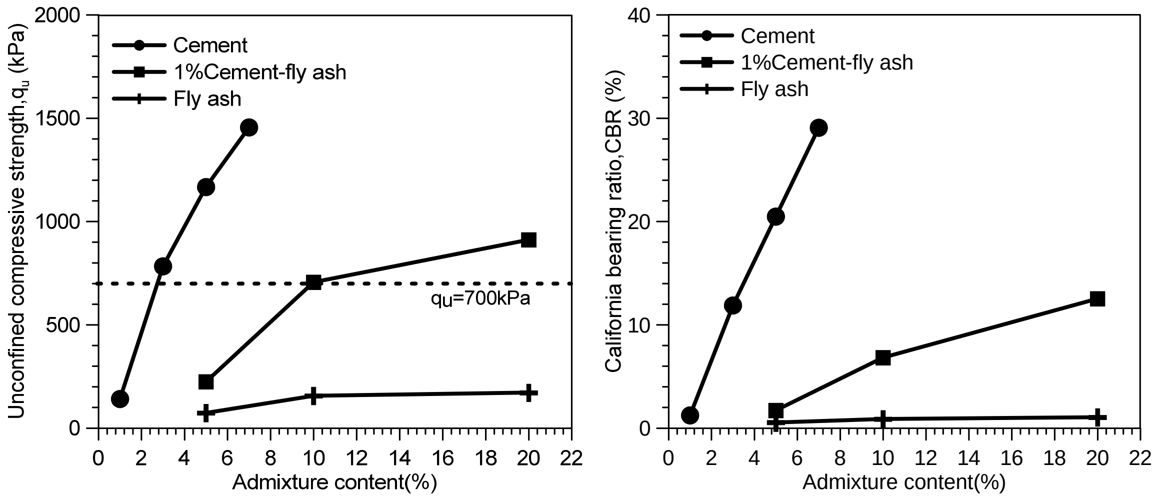
Fig. 10 Swelling and swelling pressure of unimproved and improved soils

linear relationship between the SP and maximum swelling (S_{max}) of the unimproved and improved expansive soils is shown in Fig. 10. Sridharan and Gurtug (2004) proposed a unique relationship between the swelling percentage and the swelling pressure, irrespective of the soil type, because SP (kPa) = 48.32S_{max} for kaolinite and montmorillonitic clay under a maximum swelling pressure of 1,000 kPa. In this study, there are four straight lines for different soil types that exhibit different slopes. The steepest slope was found in a specimen improved with cement followed by 1% cement with fly ash, fly ash and unimproved soil. At the same maximum swelling (S_{max}), the steeper the slope, the higher the swelling pressure. An explanation of this behavior will be discussed in the following section.

7. Unconfined compressive strength test and California bearing ratio test results

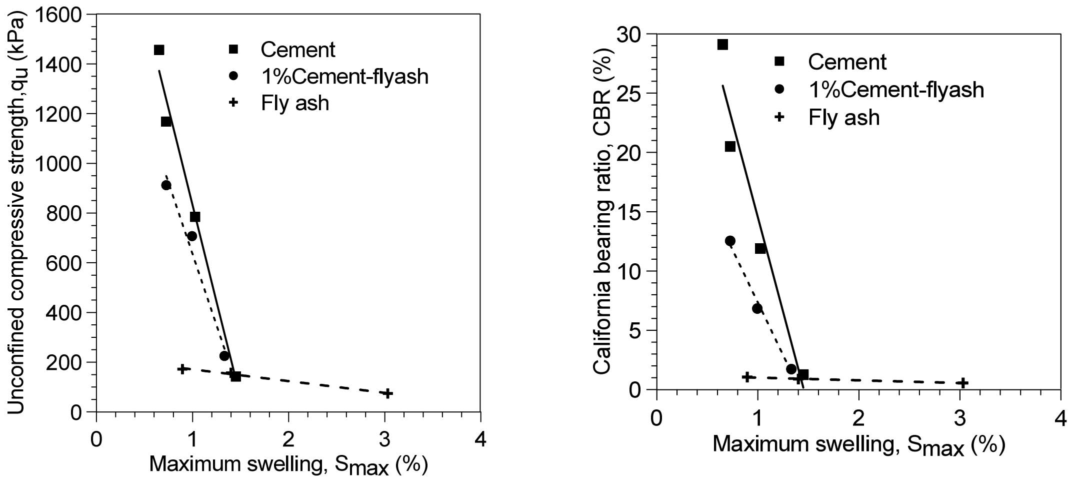
Figs. 11(a) and (b) show the effect of admixture content on the unconfined compressive strength (q_u) and California bearing ratio (CBR). The unconfined compressive strength and CBR of the unimproved soils were 45 kPa and 0.27%, respectively. These values are very low for subgrade materials. It can be observed that both the q_u and CBR of the cement-improved expansive soil significantly increased as the cement content increased. Similarly, both the q_u and CBR of 1% cement mixed with fly ash also increased moderately as the fly ash content increased. In contrast, the q_u and CBR of the fly ash-improved expansive soil slightly increased as the fly ash content increased. Therefore, it may be concluded that using fly ash as an admixture can significantly reduce the swelling percentage but cannot enhance the strength in terms of q_u and CBR. Moreover, the Department of Highway (DOH) of Thailand specifies a minimum unconfined compressive strength of 700 kPa for improved subgrade materials. The, expansive soil improved with fly ash in this study does not meet this criterion.

The maximum swelling and unconfined compressive strength and for all improved specimens are shown in Fig. 12. The figure demonstrates that the unconfined compressive strength and CBR both decrease linearly with increasing maximum swelling. Considering the same amount of maximum swelling, the specimen improved with cement provides a higher q_u and CBR than the



(a) unconfined compressive (b) CBR

Fig. 11 Effect of admixture content on unconfined compressive strength and CBR for improved soils

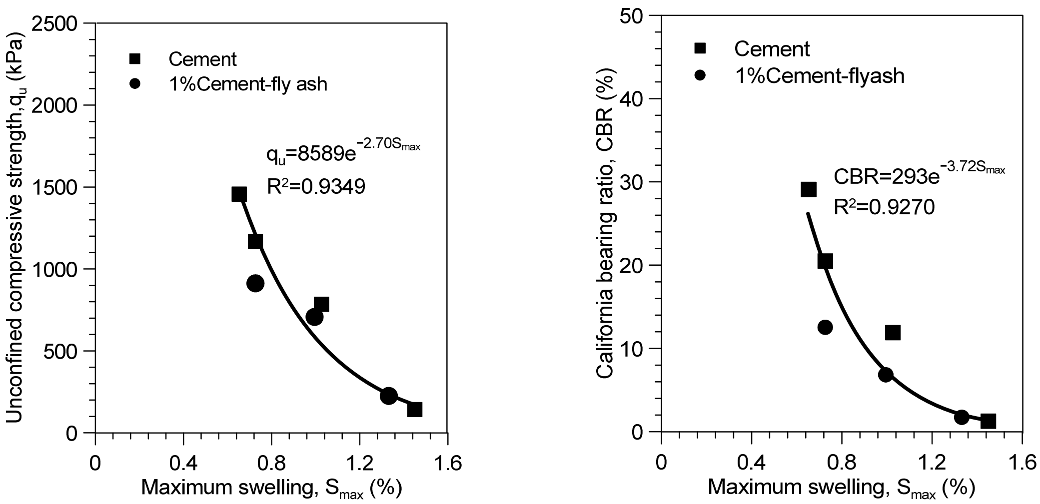


(a) unconfined compressive (b) CBR

Fig. 12 Relationship between maximum swelling and unconfined compressive strength and CBR for improved soils

other improved specimens, which implies that the specimen improved with cement is the stiffest, followed by the specimen improved with 1% cement mixed with fly ash and with fly ash. Likewise, due to the high stiffness of the cement-improved expansive soil, the specimen requires a high swelling pressure.

Focusing on the admixture content in Fig. 11, the q_u and CBR of the improved expansive soil depend largely on the binder content, including cement and 1% cement mixed with fly ash except



(a) unconfined compressive strength (b) CBR

Fig. 13 Empirical relationship of maximum swelling with unconfined compressive strength and CBR for improved soils with cement alone and 1%cement-fly ash

fly ash alone, which was previously ignored. The unique relationships between maximum swelling and q_u and CBR are presented in Fig. 13. The q_u and CBR of the expansive soil improved by cement and by 1% cement with different contents of fly ash can be predicted by the following equations

$$q_u\,(\text{kPa}) = 8589\,e^{-2.71S_{\max}} \quad (R^2 = 0.9349) \tag{4}$$

$$\text{CBR}\,(\%) = 293\,e^{-3.72S_{\max}} \quad (R^2 = 0.9270) \tag{5}$$

8. Conclusions

In this study, the swelling and shear strength characteristics of expansive soil obtained from the Mae Moh power plant, Lampang Province, Thailand, was investigated. To identify the swelling behavior of samples more clearly, experiments were conducted on improved specimens containing cement, cement mixed with fly ash and fly ash using the conventional consolidation test, the unconfined compressive strength test and the California bearing ratio. The cement content values used 1%, 3%, 5% and 7% and the fly ash content were 5%, 10% and 20%. Combination of 1% cement with 5%, 10% and 20% fly ash were also used as admixtures.

- The time taking to reach near-equilibrium of swelling for improved soils is less than those for unimproved soils because of the lower plasticity index of the improved soil specimens. Thus, the improved soils behave like kaolinite whereas the swelling behavior of unimproved soil lies between kaolinite and montmorillonite clay.
- In terms of swell potential, 3% cement is an optimum cement content that efficiently reduces the swelling of unimproved soil. For cost effectiveness, the combination of 1%

cement mixed with 8% fly ash and 14% fly ash alone are also optimum admixture, providing the same swelling of improved soils compare with 3% cement alone. Moreover, the degree of expansion of unimproved specimen can be reduced from high degree to low degree due to use of optimum admixture contents based on classification of Seed *et al.* (1962). The maximum swelling is correlated with the plasticity index of unimproved and improved expansive soils exhibiting unique exponential curve.

- The rate of secondary swelling for unimproved soil decreases from range of highly plastic montmorillonite clay to non-swelling kaolinite by improvement with of 3% to 7% cement and with 1% cement-20% fly ash. However, the specimen improved with fly ash alone is not within range of non-swelling kaolinite.
- The swelling pressure increases as the maximum swelling increases. The soil type affects the swelling pressure. The cement improved-soil with high stiffness requires high swelling pressure at the same maximum swelling.
- Fly ash is an admixture which can significantly reduce swell potential only, but it cannot improve strength characteristics (q_u and CBR). The maximum swelling can be used as a unique parameter that can predict the swelling and strength characteristics of improved and unimproved expansive soils.

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