Procedia Engineering
Volume 143, 2016, Pages 615–622

Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)

Swell-Shrink Cycles of Lime Stabilized Expansive Subgrade

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Abstract

Subgrades of expansive nature are one of the main causes of damage to road network in Australia. Consequently, lime stabilization has been widely used to reduce the swell- shrink potential of these types of soils and thus reduce the associated damage. After stabilization and compaction, the subgrade will naturally be exposed to cycles of full swell and or partial shrinkage due to climatic cycles. This paper investigates this behaviour for lime stabilized compacted expansive soil from weathered Quaternary Volcanic geological deposits located in Western Victoria; Australia. These soils were stabilized with varying percentages of hydrated lime (2, 3, 4, 6 and 8 percent) and the swell-shrink paths of both untreated and treated soils were studied. Test specimens were compacted at optimum moisture content and maximum dry density. The samples were subjected to full swell-shrink cycles under a surcharge of 25 kPa to reach structural stabilization and to simulate the impact of climatic wetting and drying cycles. Vertical deformation and swell-shrink cycle relationships for untreated and treated samples were obtained and analyzed. The results of lime stabilization indicate that equilibrium is reached after three cycles for both untreated and treated samples. In addition, results suggest that maximum deformation occurs in the second swelling cycle. Vertical deformation of untreated sample was reduced to a third after adding 2 percent lime and reduced to a sixth after adding 3 percent lime. The gradient of swelling and shrinkage path reduced to about a sixth and third when it is treated with 2 and 3 percent, respectively. The treated samples reached maximum swelling at a higher degree of saturation than the untreated sample.

Keywords: Expansive clay, Lime stabilization, swell-shrink cycles;

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Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016

doi:10.1016/j.proeng.2016.06.083

1 Introduction

Expansive soils are considered a problematic soil in many countries, especially where the climate is arid to semi-arid. Australia is one country where the swell-shrink potential of an expansive soil can damage a road network significantly and prematurely. Many studies have been performed to assess the swell-shrink potential or volume change characteristic of undisturbed expansive clays as a function of moisture content (Marinho & Stuermer 2000). In the majority of these studies, clay specimens were dried under no external pressure for one cycle to evaluate shrinkage potential. However, Haines (1923) identified different deformation stages that occur as a result of continuous drying. These stages are now known as structural shrinkage, normal shrinkage, and residual shrinkage. Further, Laboratory cyclic swell- shrink tests on reactive clays have shown that swelling deformation may decrease or increase by a factor of two when compared to the initial cycle (Tripathy, Subba Rao & Fredlund 2002). Therefore, estimating the behavior of expansive clay without considering cyclic fluctuation may underestimate the soil swelling potential. These studies suggest that equilibrium is reached after four or five cycles, indicating that the vertical displacement during swelling and shrinkage are the same after a certain number of cycles (Al-Homoud, Khedaywi & Al-Ajlouni 1995). Tripathy, Subba Rao and Fredlund (2002) studied the effect of initial condition (dry density and water content) on swell- shrink path at different surcharge pressures suggesting that the effect of initial condition on equilibrium swell-shrink path can be neglected. Gould et al. (2011) created a mathematical model to define the shrinkage curve at equilibrium cycle. This paper studies the behavior of lime stabilized compacted expansive soil under swell-shrink cycles. The optimum lime content was selected based on one dimensional swell test results. To measure these untreated and treated samples at various percentages of added lime were exposed to induced cyclic swell- shrink under a nominal pressure of 25 kPa.

2 Methodology

A series of laboratory tests were performed to identify the behavior of lime stabilized and compacted expansive soils under cycles of swell- shrink. The first series of tests were conducted to classify the expansive clay characteristics before stabilization and included specific gravity, organic content, Atterberg limit and linear shrinkage. The second series were conducted to find the optimum lime content based on swelling potential that included pH concentration, standard proctor compaction and one-dimensional swell. The third series was performed to investigate the effect of lime stabilization on the swell-shrink path under cyclic conditions.

3 Test Results

3.1 Classification

The classification of the untreated expansive soil is presented in Table 1. The selected expansive soil is classified as Clay of High plasticity (CH) with low organic content (due to the presence of remaining vegetation at shallow depth). The samples were selected from Western Victoria. The surface geology of Western Victoria is derived from weathered Quaternary age basaltic rocks (McAndrew J & Marsden M.A 1973). These soils were classified as highly to extremely expansive (Peck et al. 1992).

Characteristics	Values	Specification
Depth (m)	1-2	
Specific gravity (Gs)	2.71	ASTM-D854 (2010)
Organic content (%)	3.1	ASTM-D2974 (2000)
Grain size analysis		ASTM-D422 (2007)
Sand, Silt, Clay (%)	4, 43, 53	
Atterberg limit		ASTM-D4318 (2000)
Liquid limit, Plastic limit (%)	73, 23	
Linear shrinkage (%)	20	AS1289.3.4.1 (2008)
Soil classification (USCS)	CH	

Table 1: Physical properties of expansive clay used in study

3.2 Optimum Lime Content (OLC)

The Standard Proctor compaction test was performed according to ASTM-D698 (2000) to measure Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for the untreated expansive soil specimens. However, for the samples treated with 2, 3, 4, 6 and 8 percent lime the method by Ciancio, Beckett and Carraro (2014) was followed. The compaction results for the untreated and treated samples are presented in Table 2, which suggests that the MDD decreases and OMC increases with increasing lime content.

Lime percentage (%)	OMC (%)	MDD (kN/m^3)
0	25.0	14.9
2	26.1	14.7
3	26.5	14.6
4	26.9	14.6
6	27.8	14.5
8	28.4	14.4

Table 2: OMC and MDD results for untreated and treated samples

A set of pH concentration tests were performed on untreated and treated samples (Eades & Grim 1966). The variation of pH was measured after 0, 7, 28 and 56 days of curing and is presented in Table 3. The data shows a decrease in pH concentration as the curing period increases. This is believed to be due to the presence of organic material in the clay and formation of humic acid reducing the alkalinity of the mixture with time progressing.

A series of one-dimensional swell tests were conducted on the untreated and treated samples. The Standard Proctor compaction test results were used to compact the samples to OMC and MDD. Specimens of 45 mm in diameter and 20 mm high were then extracted and set up in an oedometer device. The specimens were saturated with distilled water under a surcharge pressure of 25 kPa, representing field stress conditions. The treated samples were allowed to cure for 1, 7 and 28 days (Zhao et al. 2014). The recorded swell results for all specimens are presented in Figure 1, which shows a significant drop in swelling after 2 percent lime was added. Furthermore, the swelling percentage approached zero after 4 percent lime was added and most of volume change occurred within 7 days of curing. These finding were similar to these of Zhao et al. (2014). Hence, from the swell test results the optimum lime content for the soil tested in this research is 4 percent.

Lime content (%)	Curing periods (days)			
	0	7	28	57
	pH concentration			
0	8.45			
2	12.19	11.85	10.78	10.21
3	12.52	12.16	11.15	10.62
4	12.76	12.47	11.59	11.06
6	12.83	12.72	12.34	11.89
8	12.90	12.77	12.55	12.29

Table 3: Variation of pH concentration vs. curing time.

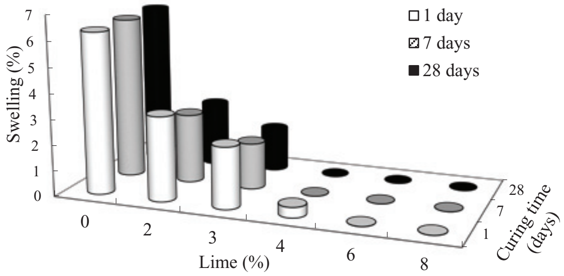


Figure1: Swelling paths of untreated and treated samples

3.3 Swell- Shrink Path

3.3.1 Swell- Shrink Cycles

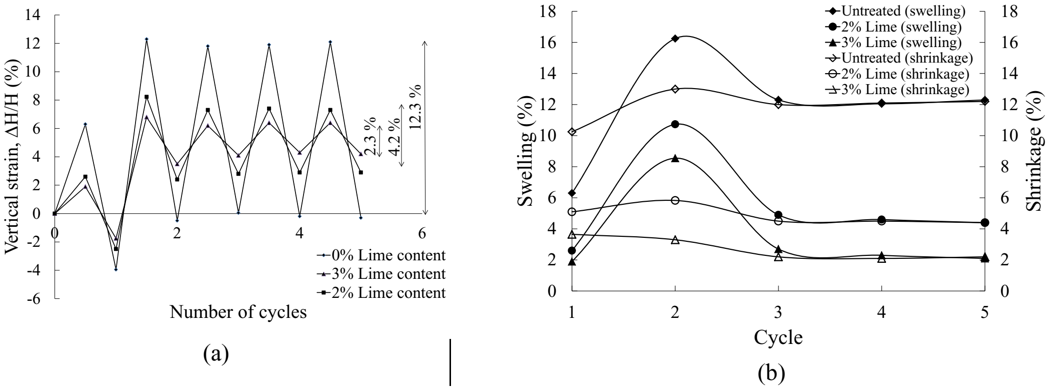
Cycles of swell- shrink tests were conducted on untreated and treated samples, with 2 and 3 percent lime content after a curing period of seven days. These tests were performed to investigate the effect of lime stabilization on swell- shrink path after reaching an equilibrium condition, which means that an equal swelling and shrinkage deformation is achieved for each cycle. The samples were compacted at optimum moisture content and maximum dry density, and subjected to cycles of swell and shrink tests according to the procedure developed by Tripathy, Subba Rao and Fredlund (2002). The treated samples were all cured for seven days and then subjected to cycles of swell-shrink. These tests were performed by using the oedometer device with some modifications to allow shrinking of the samples under a controlled pressure of 25 kPa and a constant temperature of 40 ± 5°C. The test device was kept in a temperature controlled environmental chamber during shrinkage to control and maintain the temperature at the desired value. In addition, the top cap was perforated to make it possible to inject water into the samples using a medical syringe during the swelling process. Specimens were inundated with water and allowed to swell under room temperature while vertical movements were recorded. When the swelling changes were found to be negligible, the reverse process of shrinkage commenced. Initially, water in the inner cell (around the ring cell) was removed and then the oedometer cells were placed in the chamber at a constant temperature of 40 ± 5°C. During this step, a vertical stress of 25 kPa was maintained. At the end of the shrinkage process, the first swell- shrink cycle was achieved. At the end of the shrinkage process, the sample temperature was returned to room temperature in approximately 2 or 3 hrs. The samples were again inundated with water to start the second swell-shrink cycle. This procedure was repeated until equilibrium was reached, which means that the vertical movement of swelling and shrinkage became equal to each other for each cycle. It was noted that shrinkage cracks were present in samples, which also caused a reduction in sample diameter. The cracks and reduction in diameter decreased as lime content was increased to three percent. This further indicated that lime stabilization contributed to reducing the plasticity and swelling of the expansive soils. The measured vertical deformations were converted to strain ($\Delta H / H_o$) where ΔH was the change in height due to swelling or shrinkage and H_o was the initial height. The paths of vertical deformation for the untreated and treated samples, with 2 and 3 percent lime content are presented in Figure 2.

3.3.2 Paths of Void Ratio- Water Content

At least six specimens were tested for every swell-shrink test. At the end of the fifth swell-shrink cycle, different water contents were added to each specimen using a medical syringe for both untreated and treated samples. Water content, weight, volume and associated void ratios were calculated using Equation (1). To find the void ratio for the oven dried or partially dried specimens, the volume of the specimens were measured using the kerosene technique, due to the development of cracks.

$$\gamma_d = \frac{G_s \gamma_\omega}{1+e} \tag{1}$$

By using the mathematical model proposed by Gould et al. (2011), the relationship of void ratio and water content for untreated and treated samples at equilibrium condition were measured, and is presented in Figure 3. In Figure 3, each point represents an individual specimen.



(a) (b)

Figure 2. Vertical strain and swell-shrink cycles relationship of untreated and treated samples

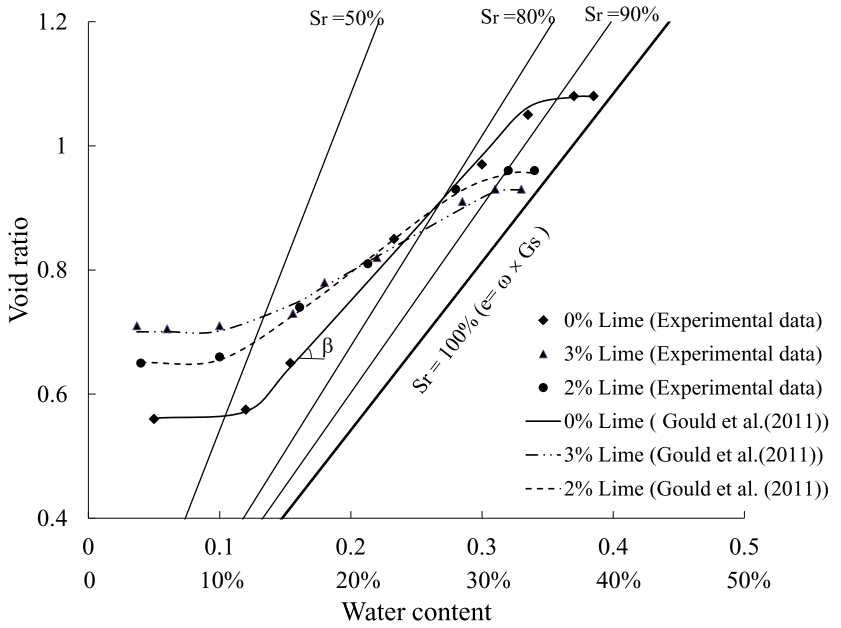


Figure 3: Void ratio - water content relationship at equilibrium condition

4 Discussion

According to the one-dimensional swelling test results, the optimum lime content for the expansive soil (derived from weathered basalt) used in this study is four percent with a minimum curing time of 7 days. The reason of this behaviour is the dropping in pH concentration values through this period (Al- Taie et al. 2015), as shown in Table 3. As a result the effect of cycles of swell-shrink on stabilized expansive soil was studied below the optimum lime content and after seven days curing. Figure 2a displays the vertical deformation during swell-shrink cycle for untreated and treated samples under a surcharge of 25 kPa. This figure shows that the maximum swelling occurs in second cycle. This means if a pavement is designed relying on the results of first cycle; it will be exposed to high swelling in the second cycle, which can result in premature damage or roughness. Figure 2b shows the equilibrium condition occurring at either cycle three or four for both untreated and treated samples. However, based on small swell-shrink difference after cycle three, one can assume the equilibrium practically occurs at the end of cycle three. The vertical deformations at this condition for untreated and treated (2 and 3 percent lime) were 12.3, 4.2 and 2.3 percent, respectively. This means that the vertical deformation of the untreated sample was reduced to a third after adding 2 percent lime and reduced to a sixth after adding 3 percent lime. It is evident from Figure 4 that the shape of swell- shrink paths for untreated and treated soil is an S curve, where middle phase is almost linear. For the untreated sample, the swell- shrink path is approximately parallel to the saturation line and the gradient of this line (α) is 0.82 (equation (2)). β is the gradient of swell-shrink path in term of void ratio and water content (Figure 3)

$$\alpha = \left(\frac{\partial e}{\partial e_w}\right)_\sigma = \beta / Gs \tag{2}$$

where $\beta = \left(\frac{\partial e}{\partial \omega}\right)_\sigma$ and $e_w = G_s \times \omega$

However, the swell-shrink path for the treated sample, as compared with untreated sample, becomes smaller and moves toward the saturation line with a smaller gradient (α). In addition, as lime content increases, the swell- shrink path becomes flatter. The values of α for samples stabilized with 2 and 3 percent lime are 0.50 and 0.33, respectively. Figure 3 also shows that the major volume change occurs through the linear portion of the S- shaped curve. For untreated sample, the major volume change starts when the sample reaches approximately 60% saturation and the volume change can be neglected after reaching 85% saturation. However, for the treated sample this significant and major portion of volume change begins at approximately 50% saturation and the volume change can be ignored after reaching 90% saturation. The reason for this behaviour is due to structural changes in pore structure of treated clay after adding lime. The value of swelling of untreated sample is higher than of treated sample which means that the void ratio of untreated sample is higher than of treated sample. The relationship of void ratio and degree of saturation is an inverse relationship. This means the same amount of water causes a different degree of saturation. And hence, the degree of saturation of the treated samples would be higher than of untreated sample.

5 Conclusion

A set of cycles of swell-shrink tests were conducted on untreated and lime stabilized expansive clays. These tests were performed under a surcharge pressure of 25 kPa. The results show the following:

1- As soon as the untreated and treated samples reached equilibrium, the swell- shrink path became elastic, where the vertical displacement due to swelling and shrinkage are the same.
2- Both untreated and lime stabilized samples reached an equilibrium condition after three cycles.
3- The maximum swelling occurred at the second cycle for all samples tested. This suggests review of current design procedures that do not evaluate or consider cyclic movements are underestimating swell-shrink potential.
4- Vertical deformation of untreated sample was reduced to a third after adding 2 percent lime and reduced to a sixth after adding 3 percent lime.
5- The gradient of swelling and shrinkage path for the untreated expansive soil reached 0.82, while this gradient reduced to about a sixth and third when it was treated with 2 and 3 percent lime, respectively. This means that shape of swelling and shrinkage became flatter after lime was added.
6- For the untreated samples, the critical volume change occurred between 60 and 85% saturation. Whereas, the critical volume change occurred between 50 and 90% saturation for the lime treated samples. Therefore, the treated samples reached maximum swelling at a higher degree of saturation than the untreated samples.
7- For untreated and treated samples, it is important to measure swelling value from the first cycle, for short term, to simulate the field condition after compaction. It is also important to consider the climate cycles to simulate the field condition for long term.

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