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Effect of Lime on Compaction, Strength and Consolidation Characteristics of Pontian Marine Clay

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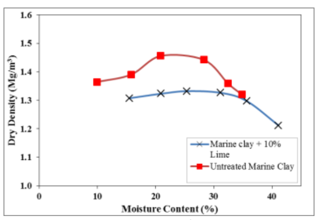
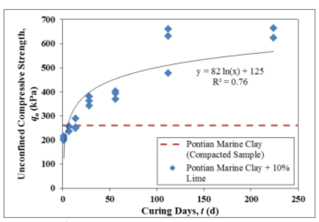
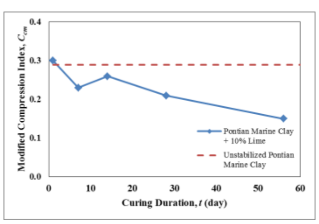
Graphical abstract



Compaction curves of unstabilized and lime stabilized Pontian marine clay



Unconfined compressive strength versus curing duration



Modified compression index versus curing duration

Abstract

Marine clay is a problematic construction material, which is often encountered in Malaysian coastal area. Previous researchers showed that lime stabilization effectively enhanced the engineering properties of clay. For soft clay, both strength and consolidation characteristics are equally important to be fully understood for design purpose. This paper presented the effect of lime on compaction, strength and consolidation characteristics of Pontian marine clay. Compaction, unconfined compression, direct shear, Oedometer and falling head permeability tests were conducted on unstabilized and lime stabilized samples at various ages. Specimens were prepared by compaction method based on 95 percent maximum dry density at the wetter side of compaction curve. It was found that lime successfully increased the strength, stiffness and workability of Pontian marine clay; however, the permeability was reduced. Unconfined compressive strength of stabilized soil was increased by 49 percent at age of 56 days whereas compressibility and permeability was reduced by 48 and 67 percent, respectively. From laboratory tests, phenomenon of inconsistency in engineering characteristics was observed for lime stabilized samples below age of 28 days. This strongly proved that lime stabilized soil underwent modification phase before stabilization phase which provided the long term improvement.

Keywords: Cohesion; compression index; compressive strength; internal friction angle; lime stabilization; marine clay; permeability

Abstrak

Tanah liat marin yang merupakan bahan pembinaan bermasalah, sering didapati di persisiran pantai Malaysia. Penyelidik terdahulu melaporkan bahawa penstabilan menggunakan kapur boleh meningkatkan sifat-sifat kejuruteraan tanah liat secara berkesan. Bagi tanah liat lembut, ciri-ciri kekuatan dan penyatuan yang sama penting untuk difahami sepenuhnya demi tujuan reka bentuk. Kertas kerja ini membentangkan kesan kapur terhadap sifat pemadatan, kekuatan dan penyatuan tanah liat marin Pontian. Ujian pemadatan, ujian mampatan tak mengurung, ujian ricih terus, ujian Oedometer dan ujian ketelapan turus menurun dikendalikan atas sampel yang distabilkan dan tidak distabilkan dengan kapur pada pelbagai peringkat usia, yang telah disediakan dengan kaedah pemadatan. Didapati bahawa kapur berjaya meningkatkan kekuatan, kekerasan dan kebolehkerjaan tanah liat marin Pontian. Akan tetapi, ketelapan air dikurangkan. Kekuatan mampatan tak terkurung ditingkatkan sebanyak 49 peratus pada usia 56 hari manakala kebolehmampatan dan ketelapan air dikurangkan sebanyak 48 peratus dan 67 peratus, masing-masing. Dari pelbagai ujian di atas, fenomena peningkatan yang tidak menentu diperhatikan dalam keputusan bagi sampel di bawah usia 28 hari. Ini membukitkan bahawa tanah liat distabilkan dengan kapur mengalami fasa pengubahsuaian sebelum fasa penstabilan yang menyumbang kepada peningkatan sifat tanah untuk jangka panjang.

Kata kunci: Kejelekitan; indeks pengukuhan; kekuatan mampatan; sudut rintingan dalam; penstabilan kapur; tanah liat marin; ketelapan air

1.0 INTRODUCTION

Marine clay is problematic and challenging soft clay for geotechnical engineers as it has low strength, low permeability and high compressibility, which may cause continuous settlement and damages to the foundation and structures above [1-5]. Marine clay is widely encountered in coastal areas in Malaysia and they are normally very thick, which is up to 30m [6]. Previous researches showed that hydrated lime can effectively enhance the engineering properties of clayey soil [7-11]. Lime stabilization was practiced over 5000 years ago and currently it is widely applied in countries such as China, India, Sweden, Japan and

United States [12]. However, according to Chan and Lau (1973), the first lime stabilization work in Malaysia was conducted in Kuala Terengganu airfield in order to form a six inches lime stabilized base as a main structural element of pavement [13].

Lime stabilization was divided into two phases, namely modification and stabilization. In modification stage, lime modified the clay texture, reduced plasticity and improved the compaction characteristics of clayey soil. Afterwards, the long term strength improvement of clayey soil due to lime was only effectively developed in lime stabilization stage [11].

Many researchers concentrated on the physical and strength properties of lime stabilized soils [8-10, 14]. Some researchers focused on the consolidation properties of lime stabilized soil [15, 17]. For high compressibility clay, the study on both strength and consolidation properties are essential in design purpose, therefore this comprehensive study covered the strength and consolidation properties for Pontian marine clay in order to provide a complete information for design purpose. Other than that, it was also to establish a clear modification and stabilized stage for lime stabilized Pontian marine clay.

2.0 EXPERIMENTAL

Pontian marine clay from Sg. Penerok T/Kiri in Pontian, Johor, Malaysia was selected in this test. Based on BS 1377-1, the soil was oven-dried at 50 °C, crushed and sieved to pass 2 mm sieve. The liquid limit and plastic limit of Pontian marine clay was 62 percent and 30 percent, respectively. It was classified as clay with high plasticity (CH), with composition of 39 percent clay, 51 percent silt and 10 percent sand. The pH of Pontian marine clay was 7. From initial consumption of lime test in accordance to Clause 5 in BS 1924-2: 1990 [18], the initial consumption of lime was 4 percent. Hydrated lime from Limetreats, Pasir Gudang in Johor was selected as the stabilizer.

Laboratory tests were carried out on both lime stabilized and unstabilized compacted samples at different ages in order to evaluate the effect of lime on compaction, strength and consolidation characteristics of Pontian marine clay. Compaction tests were performed on 50 ºC oven-dried samples using a 1 litre mould by applying 27 blows on each three layers of soil using a 2.5 kg rammer. Dry density versus moisture content curves were plotted for unstabilized and stabilized samples with 10 percent of hydrated lime, in order to determine the optimum moisture content and maximum dry density for each condition. Unconfined compressive test and direct shear test were conducted to investigate the effect of lime on shear strength of Pontian marine clay. Meanwhile the effect of lime on modified compression index and permeability of Pontian marine clay were studied by oedometer test and falling head permeability test, respectively. All the laboratory tests were conducted on compacted samples in accordance to BS 1377 (1990) [19] and BS 1924 (1990) [18]. The falling head permeability was conducted in accordance to method proposed by Head [20]. The compacted samples were prepared by compaction of soil or soil-lime mixture to pre-determined density, based on 95 percent dry density on the wetter side of compaction curves. Unstabilized sample were tested one day after sample preparation whilst the stabilized samples were tested at age 1, 14, 28 and 56 days. For unconfined compressive test, stabilized samples at age 112 and 224 days were also tested.

3.0 RESULTS AND DISCUSSION

3.1 Compaction Characteristics

Lime content selected for stabilized marine clay in this research was based on typical lime content in lime column reported by previous researches, which was 10 percent [21]. Compaction test was conducted on Pontian marine clay stabilized with 10 percent of lime and unstabilized sample, in order to investigate the initial reactions of lime on Pontian marine clay in modification process. It was found that the relative density of unstabilized and lime stabilized Pontian clay was 1.82 Mg/m^3 and 1.72 Mg/m^3, respectively. Figure 1 shows the compaction curves of unstabilized and stabilized Pontian marine clay. With lime stabilization, the maximum dry density was reduced from 1.48 Mg/m^3 to 1.34 Mg/m^3 at same compaction effort. However, strength gain afterwards normally exceeded the compensation on reduction of maximum dry density. Furthermore, lime stabilization increased the optimum moisture content from 23.5 percent to 28 percent. Compaction curve was flattened showing that good densities can be achieved in a wider range of moisture content [12]. Lime stabilization increased the optimum moisture content. This enabled the soil to be compacted well in wetter condition with maximum dry density achieved therefore increased the workability of soil at site.

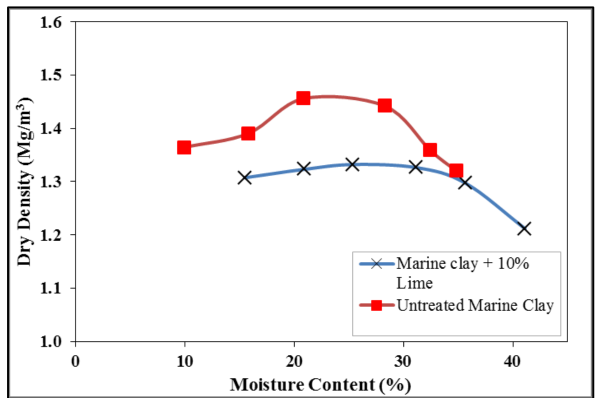


Figure 1 Compaction curves of unstabilized and stabilized Pontian marine clay

3.2 Strength Characteristics

Effect of lime stabilization on strength characteristics of Pontian marine clay, which comprised unconfined compressive strength and shear strength parameter from direct shear test, were discussed,. Influence of curing duration on performance of lime stabilization was also evaluated.

3.2.1 Unconfined Compressive Strength

For unstabilized Pontian marine clay, unconfined compressive strength was 261 kPa and failure strain of 3.27 percent was recorded. Table 1 shows the results from unconfined compressive test for lime stabilized Pontian marine clay sample at various ages, ranged from 1 day to 224 days, cured at room temperature 28± 2°C. Figure 2 shows the Influence of curing duration on unconfined compressive strength of lime stabilized Pontian marine clay. Initially, the average unconfined compressive strength of stabilized sample was lower compared to unstabilized sample, from age 1 to 7 days. However, unconfined compressive strength of lime stabilized Pontian marine clay increased gradually with ages and surpassed the strength of unstabilized sample at age 14 days. After that, strength increase rate was more rapid and reached 1.5 and 2.5 times unconfined compressive strength unstabilized sample at age 56 and 224 days, respectively. Early slow increase might because the strength of stabilized soil was not well-developed in modification stage at early ages. Subsequently, after age 14 days, the formation of silica gel in pozzolanic reaction at stabilization stage which provided long term strength gain of stabilized soil had significantly increased the strength of stabilized soil [13].

It was found that the strength increase of lime stabilized Pontian marine clay continued after months. The pozzolanic reactions may continue in 1 to 5 years or more with the condition that there is adequate residual lime and availability of silica and alumina [8, 14, 22, 23]. Previous researchers suggested that increase of strength was approximately linear with the logarithm of time [14, 24]. The relationship between unconfined compressive strength of lime stabilized Pontian marine clay and curing duration is shown in Figure 2. A general pattern of decreasing failure strain with the increasing of unconfined compressive strength was found on lime stabilized Pontian marine clay as shown in Figure 3. The pattern was similar to findings by previous researcher on the measured strains at failure in different stabilized soil, namely peat, gyttja and clay [25].

Table 1 Results from unconfined compressive test for lime stabilized Pontian marine clay

Age t (day)	Average Unconfined Compressive Strength $q_{u,col}$ (kPa)	Average Failure Strain (%)
1	207	2.00
7	249	2.00
14	264	1.85
28	362	1.30
56	389	1.20
112	590	1.23
224	645	1.45

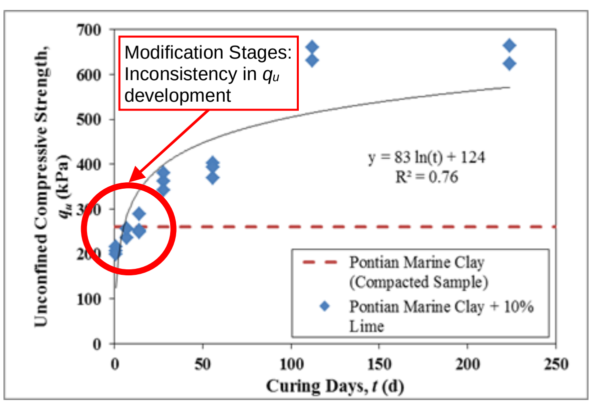


Figure 2 Influence of curing duration on unconfined compressive strength of lime stabilized Pontian marine clay

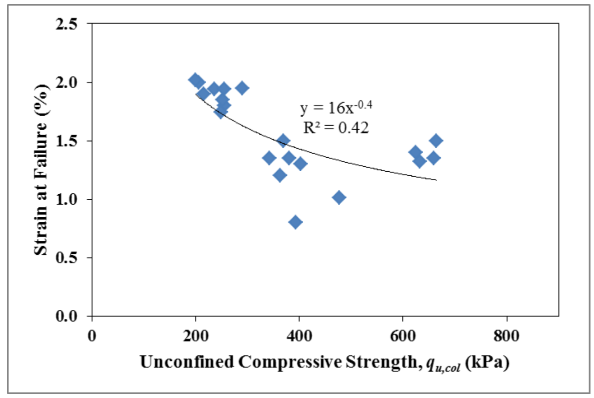


Figure 3 Influence of strength on failure strain of lime stabilized Pontian marine clay

3.2.2 Young Modulus

Young's modulus of lime stabilized Pontian marine clay, E_{50}, is defined as secant modulus of lime stabilized soil at 50 percent of maximum unconfined compressive strength. The results were based on unconfined compression test. Young's modulus for lime stabilized Pontian marine clay at different ages is shown in Figure 4. It was observed that Young's modulus increased with curing duration. Young's modulus for lime stabilized soil at aged 56 days varied from 34 to 49 MPa with an average of about 40 MPa. The correlation between Young's modulus and cohesion of lime stabilized Pontian marine clay is shown in Figure 5. Young's modulus of lime stabilized Pontian marine was about 180 times of stabilized soil cohesion, based on results from unconfined compression test. It was higher than suggested Young's modulus value by Ekstrom (1992), in which the Young's modulus for lime stabilized soil was between 50 to 150 times of stabilized soil cohesion [22].

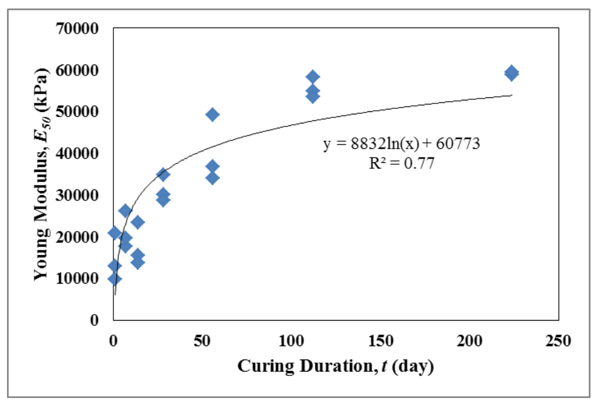


Figure 4 Young modulus, E_{50} for lime stabilized Pontian marine clay at different ages

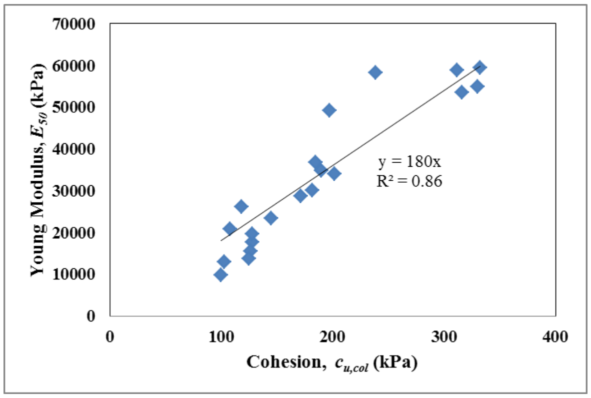


Figure 5 Correlation between Young modulus and cohesion for lime stabilized Pontian marine clay

3.2.3 Shear Strength Parameters From Direct Shear Test

The relationships between shear stress and lateral displacement for unstabilized and lime stabilized Pontian marine clay samples obtained from direct shear test results, are shown in Figure 6 to 8. It was observed that lime stabilization increased the shear strength of Pontian marine clay with ages. Other than that, stabilized samples with longer curing duration behaved more brittle compared to samples at younger ages under same normal pressure. The failure strain of stabilized soil decreased with ages. Table 2 and Figure 9 summarized the shear strength parameters for unstabilized and stabilized sample. It was observed that cohesion for stabilized sample increased drastically from age 1 day to age 7 days, afterwards increased slowly and achieved 109 kPa at age 56 days, which was 250% higher than unstabilized sample. Friction angle also increased with the introduction of lime. At age 0 to 14 days, the increase of friction angle was not steady as lime-soil mixture was still in modification phase. Increase of frictional angle was due to the cation exchange and flocculation process which changed the plate-like molecular structure of natural clay to needle-like interlocking structure [13, 26, 27]. Afterwards the friction angle of stabilized sample reached 30.5° at age 56 days, which was 10.3° more than the unstabilized sample. Further increase of shear strength and friction angle after age 14 days was resulted from crystallization process during stabilization phase.

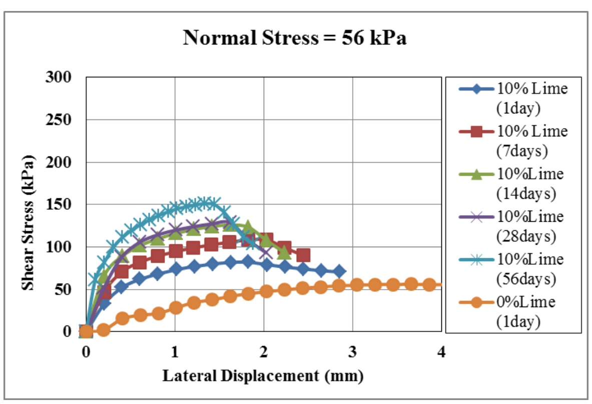


Figure 6 Shear stress and displacement relationships of lime stabilized Pontian marine clay compacted samples with different ages (normal stress of 56 kPa)

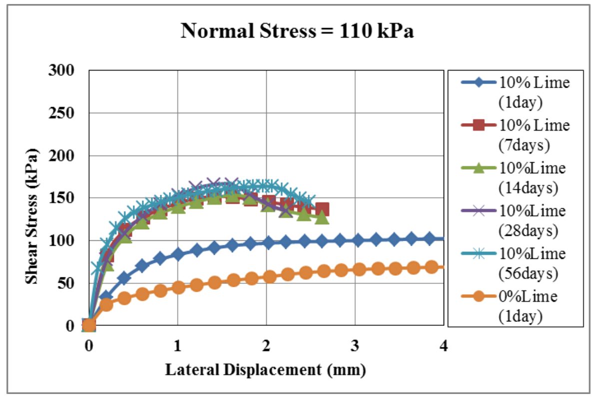


Figure 7 Shear stress and displacement relationships of lime stabilized Pontian marine clay compacted samples with different ages (normal stress of 110 kPa)

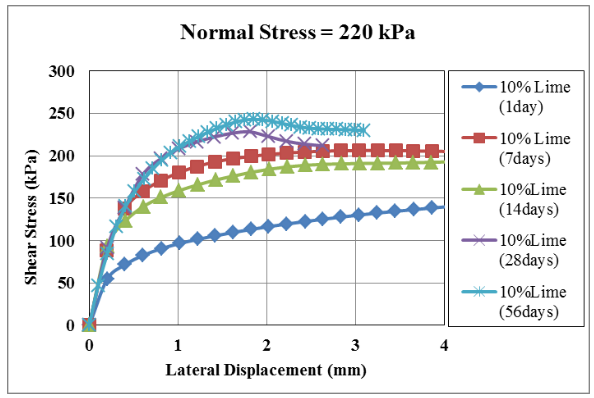


Figure 8 Shear stress and displacement relationships of lime stabilized Pontian marine clay compacted samples with different ages (normal stress of 220 kPa)

Table 2 Shear Strength parameters of unstabilized and lime stabilized Pontian marine clay

Sample	Age t (day)	Cohesion c (kPa)	Friction Angle φ (°)
Pontian Marine Clay	1	31	20.2
Pontian Marine Clay + 10% Lime	1	53	24.4
	7	95	26.8
	14	102	23.4
	28	107	30.0
	56	109	30.5

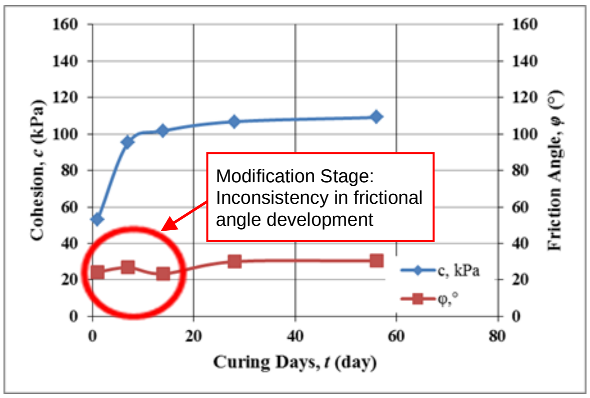


Figure 9 Undrained cohesion and friction angle of lime stabilized Pontian marine clay with ages

3.3 Consolidation Characteristics

Effect of lime stabilization on consolidation characteristics of Pontian marine clay, namely compressibility and permeability, were discussed. Influence of curing duration on performance of lime stabilization was also evaluated.

3.3.1 Compressibility

The compressibility of lime stabilized Pontian marine clay was investigated by modified compression index obtained from modified compression curve (e/e_0 vs. log σ'), in order to minimize the inaccuracy in comparison on compressibility for sample at different ages due to different initial voids ratio [15]. Modified compression index, C_{cm} can be obtained using Equation 1:

$$C_{cm} = C_c / e_0 \qquad \text{Equation 1}$$

The initial void ratio, e_0 and modified compression index, C_{cm} for unstabilized and lime stabilized Pontian marine clay was summarized in Table 3. Figure 10 shows that initially the lime stabilized Pontian marine clay had higher modified compression indexes compared to unstabilized sample; however modified compression index reduced to 0.24 at age 7 days and then increased to 0.26 at age 14 days. The inconsistency of modified compression index between ages of 1 to 14 days was because lime stabilized samples were in modification state. However, after age of 14 days, the modified compression index for lime stabilized Pontian marine clay decreased significantly with ages. A reduction of 48 percent on the modified compression index compared to unstabilized sample was achieved at age 56 days. This indicated that the stiffness of lime stabilized Pontian marine clay increased with ages, due to the facts that bonding resulted from pozzolanic reaction during stabilization process increased the resistance on settlement for lime stabilized sample.

Table 3 Modified compression index of unstabilized and lime stabilized Pontian marine clay compacted samples

Sample	Age t (day)	Initial Void Ratio e_0	Modified Compression Index C_{cm}
Pontian Marine Clay	1	1.41	0.29
Pontian Marine Clay + 10% Lime	1	1.19	0.30
	7	1.08	0.24
	14	1.31	0.26
	28	1.11	0.21
	56	1.20	0.15

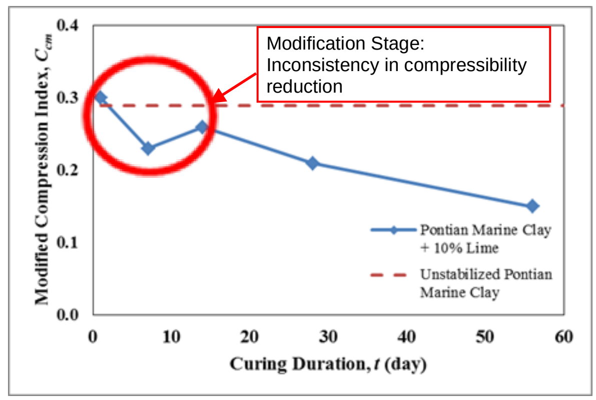


Figure 10 Modified compression index of lime stabilized Pontian marine clay (compacted samples) with ages

3.3.2 Permeability

Coefficient of permeability, k obtained from falling head permeability test was used to study the effect of lime on permeability characteristics of Pontian marine clay. The average coefficients of permeability, k of lime stabilized sample are summarized in Table 4. Pontian marine clay which had permeability of 2.808 x 10^{-7} m/s, was classified as low permeability soil with poor drainage characteristics [28]. Generally, it was discovered that the permeability of sample prepared by compaction method for both lime stabilized and unstabilized samples were higher and classified as low permeability soil with good drainage characteristics. Compared to unstabilized Pontian sample prepared by compaction method, the permeability of lime stabilized sample was lower and decreased with ages as shown in Figure 11. A reduction of 67 percent was observed for lime stabilized Pontian marine clay at age of 56 days. Similar behaviour was found by previous researchers [15, 29, 30]. The hydrated lime and clay underwent pozzolanic reaction in stabilization phase and produced calcium silicate gel which is tough water-insoluble. The clay lumps were immediately coated and bind by silicate gel consequently filled up the void space and blocked the soil pores [31]. As pozzolanic reactions continued with ages, the permeability of lime stabilized sample reduced with ages.

Table 4 Coefficient of permeability of lime stabilized Pontian marine clay (compacted sample) with ages

Sample	Age *t* (day)	Coefficient of Permeability *k* (mm/s)
Pontian Marine Clay + 10% Lime	7	3.153 x 10^{-06}
	14	3.195 x 10^{-06}
	28	2.446 x 10^{-06}
	56	1.485 x 10^{-06}

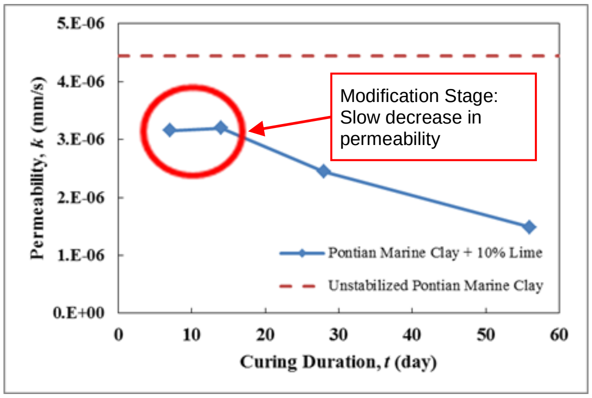


Figure 11 Permeability of lime stabilized marine clay with ages

■4.0 CONCLUSION

In general, lime stabilization significantly improved the strength and consolidation characteristics of Pontian marine clay. It was found that lime stabilization increased the optimum moisture content of Pontian marine clay from 23.5 percent to 28 percent. However, the maximum dry density was reduced from 1.48 Mg/m^3 to 1.34 Mg/m^3. At age 56 days, the unconfined compressive strength was increased by 49 percent. For the shear strength parameters from direct shear test, lime stabilization increased the cohesion from 31 kPa to 109 kPa and internal friction from 20.2° to 30.5°. The stiffness of Pontian marine clay was also improved; the modified compression index at age 56 days was reduced by 48 percent. However, the permeability was decreased by 67 percent at age 56 days. Increment of unconfined compressive strength was observed after curing duration of 224 days. This was because the lime stabilization process continued after 56 days with the existence of adequate residual lime and availability of silica and alumina.

It was observed that most of the soil parameters behaved inconsistently at age of 1 to 14 days for lime stabilized Pontian marine clay. Similar phenomenon in various tests above strongly proved that lime-soil mixture was still in modification phase at early ages. The significant improvement on unconfined compressive strength and consolidation characteristics with the remarkably decrease of permeability at age 28 days ascertained that the hydrated lime-soil mixture was undergoing stabilization phase which can produce long term increase of shear strength.

In conclusion, lime successfully improved the compaction, strength and consolidation characteristics of Pontian marine clay. However, curing duration is an important parameter in determining the success of lime stabilization. It is important to understand and differentiate the short term and long term improvement by modification and stabilization phase, respectively.

Acknowledgement

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