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## LIME STABILIZED MALAYSIAN COHESIVE SOILS

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**Abstract:** This paper highlights the essential tests for assessing the suitability of lime for stabilizing soils and typical changes in soil characteristics due to modification and stabilization processes with respect to mineralogical influences. The reasoning behind the mechanism of lime clay reaction on the compressive strength development of stabilized soils has been established. Clay with acidic origin exhibit less significant increase in compressive strength compared to clay with high intensity of kaolinite and with alkaline origin. In general, lime contents instituted, ranging from 3% to 6%, have contributed to a significant increase in unconfined compressive strength, from 2.5 to 11 times of the untreated soils. The formation of calcium aluminates silicate hydrate (CASH) observed from XRD test, after 14 days, indicates the early formation of new product, due to lime-soil reaction. The effectiveness of stabilization process has been found to be dependent on the quality of the lime, clay fraction, mineralogy and the alkalinity of the soil.

Keywords: *Lime; Stabilization; Modification; Cementation; Mineralogy*

**Abstrak:** Kertas kerja ini menumpukan kepada beberapa ujian utama bagi menilai kesesuaian bahan kapur untuk menstabilkan tanah dan melihat kepada perubahan dalam ciri-ciri tanah terstabil hasil daripada proses pengubahsuaian dan penstabilan dengan pengaruh minerologi. Punca disebalik mekanisma tindakbalas antara kapur dan tanah liat keatas perkembangan dalam kekuatan mampatan tanah terstabil telah dikenalpasti. Tanah liat yang berasal dari keadaan berasid kurang menunjukkan peningkatan dalam kekuatan mampatan berbanding dengan tanah liat yang mempunyai intensiti kaolinit yang tinggi dan berkeadaan alkali. Secara amnya julat kandungan kapur yang digunakan adalah antara 3% ke 6%, telah menunjukkan pertambahan kekuatan mampatan tak terkurung dari 2.5 ke 11 kali ganda berbanding tanah tak terstabil. Pembentukan kalsium aluminat silikat terhidrat (CASH) daripada ujian XRD, selepas 14 hari, menunjukkan tanda pembentukan awal bahan baru dalam tindakbalas tanah dan kapur. Keberkesanan proses penstabilan kapur didapati bergantung kepada kualiti kapur, kandungan tanah liat, minerologi dan alkaliniti tanah.

Katakunci: *Kapur; Penstabilan; Pengubahsuaian; Pengikatan; Minerologi.*

## 1. Introduction

Malaysia is endowed with rich limestone resources and has sufficient supply of the lime. Limestone formations are widespread in Pulau Langkawi, Kinta Valley, Gua Musang and Kuala Lumpur areas. Through this local advantage, the use of lime stabilisation method presents a good prospect for acceptance as a cost-effective soil stabilisation. The first lime stabilisation work in Malaysia to form a six - inch lime stabilised base as a main structural element of a pavement was in the construction of Kuala Trengganu airfield (Chan and Lau , 1973).

Many researchers considered the physical characteristics of the soil and construction aspects to establish the effectiveness of lime stabilization (Bell, 1988; Heath, 1992; Rogers and Glendenning, 1996; Sherwood, 1993). Extending such research, it is important to investigate further on the soil mineralogical aspect of lime stabilised soil since the primary component of soil-lime reaction involves the development of new products. Failing to understand the mechanism of soil-lime reaction will somehow lead to poorer effectiveness in lime stabilisation method.

## 2. Materials

Soil samples from various locations in Peninsular Malaysia were collected for the study. The soil samples were chosen to represent plasticity index ranging from 20 to 50 and clay fraction from 10 to 50 percent. Hydrated lime product from Limetreat, Pasir Gudang in Johor was used as an active additive. The lime was kept in an airtight container to preserve its originality.

### 2.1 Soil

Clay soils from five locations in Peninsular Malaysia, were acquired namely Kulai and Pelepas in Johor, Sg. Buluh in Selangor, Tapah Kaolin in Perak and Jerangau in Terengganu. The properties of the soils are given in Table 1.

### 2.2 Lime

Two types of lime commonly used in stabilisation are hydrated lime [ $\text{Ca}(\text{OH})_2$ ] and quicklime [ $\text{CaO}$ ] (Ingles, 1970). These limes would modify the soil through cation exchange and stabilized it after the modification process has completed. The chemical content of hydrated lime used in this study are given in Table 2.

### 3. Laboratory Tests

Three types of laboratory tests were carried, i.e. classification, shear strength and mineralogical investigation. The classification tests include the determination of optimum lime contents and suitability of lime and soil for stabilisation work. The strength test indicates the effect of stabilised age on soil strength rate of increase. The mechanism for such increase was further investigated through mineralogical studies using X-Ray Diffraction (XRD) and Scanning Electron Micrographs (SEM).

Table 1: Properties of soils used in this study

	Kulai clay	Pelepas marine clay	Sg. Buluh clay	Tapah Kaolin	Jerangau clay
<b>1. Physical properties</b>					
Natural moisture content (%)	33	121	34	48	39
Particle density	2.73	2.74	2.75	2.64	2.69
Liquid limit (%)	52	56	71	93	70
Plastic limit (%)	28	24	31	43	25
Plasticity index (%)	24	32	40	50	45
UCS (kPa)	38.1	24.5	35.5	24.4	150.1
<b>2. Particle size distribution</b>					
Sand	43.2	34.0	0.5	6.0	0.4
Silt	45.4	27.7	68.2	57.6	55.4
Clay (CF)	11.4	38.3	31.3	36.4	44.2
Clay activity ( $A_c$ )	2.11	0.84	1.28	1.37	1.02
<b>3. Soil classification</b>					
BSCS	MH	CH	CV	CE	CV
USCS	CH	CH	CH	MH	CH
ASCS	A-7-6	A-7-6	A-7-5	A-7-5	A-7-6
<b>4. Chemical properties</b>					
Organic content (%)	0.30	0.75	0.42	0.24	0.33
pH at 20% solids	4.3	8.4	3.5	4.5	4.9

Table 2: Chemical contents of hydrated lime

Chemical contents	Quantity
Calcium Hydroxide	[Ca(OH) <sub>2</sub> ] 90 % min
Magnesium Oxide	[MgO] 2 % max
Calcium Carbonate	[CaCO <sub>3</sub> ] 6 % max
Arsenic	[As] 10 p.p.m. max
Lead	[Pb] 5 p.p.m. max

## 4. Results and Discussion

### 4.1 Lime Fixation Capacity (LFC)

The changes in plastic limit of the treated materials of different lime percentage for the five different sites are shown in Figure 1. The different in lime fixation capacity is dependent on the clay content and its cation exchange capacity.

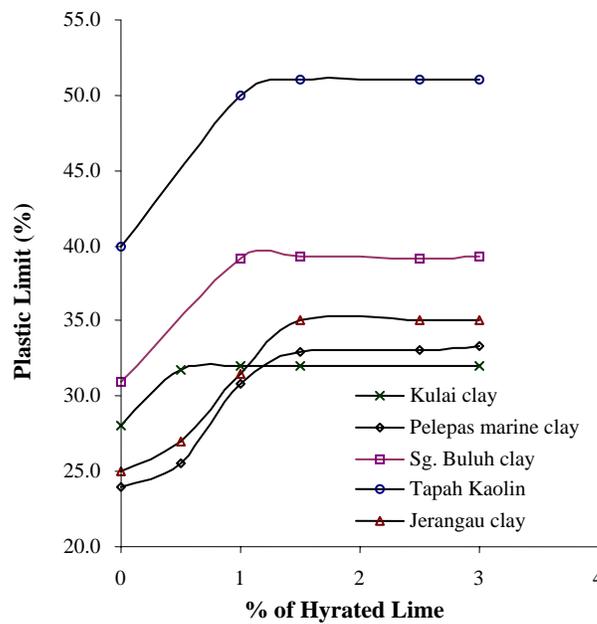


Figure 1: Lime fixation capacity of various types of materials with different additions of lime.

### 4.2 Lime Suitability

Clause 5.4.6 in BS 1924: Part 2: 1990, has suggested that the average pH of hydrated lime to be used should be within the acceptable limits of pH value from 12.35 to 12.4 at the corrected temperature of 25°C. The quality of the lime used in this study complies with that proposed guide in BS 1924. i.e. with an average pH of 12.38.

4.3 Available Lime Content (ALC)

The average ALC in terms of equivalent CaO was 65.8%, which is above the minimum requirement of 60%. The average Ca(OH)<sub>2</sub> content was 86.8%, which is also above the minimum requirement of 80% for hydrated lime.

4.4 Initial Consumption of Lime (ICL)

Table 3 presents the summary of ICL test results on various types of soils at corrected temperature of 25°C.

4.5 Determination of Optimum Lime Content

In order to establish the mix design for lime stabilization, one has to consider the two processes involved namely modification and stabilization. Minimum lime content for modification was established using lime fixation capacity (LFC).

Table 3: pH values for the ICL tests.

Soil Types	Percentage of Lime Content							
	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
Kulai clay	4.3	11.7	12.3	12.4	12.4	12.4	12.4	12.4
Pelepas marine clay	8.4	10.9	11.8	12.2	12.3	12.3	12.4	12.4
Sg. Buluh clay	3.5	12.1	12.1	12.3	12.3	12.4	12.4	12.4
Tapah Kaolin	4.5	10.6	11.4	12.3	12.4	12.4	12.4	12.4
Jerangau clay	4.9	10.5	11.8	12.2	12.3	12.4	12.4	12.4

For stabilization purposes, the minimum lime content to initiate the process can be obtained using ICL test. More lime was required for full stabilization and the lime required can be established from the strength test. UCS tests were performed on lime stabilize soils at various age and lime content. The results are shown in Figure 2.

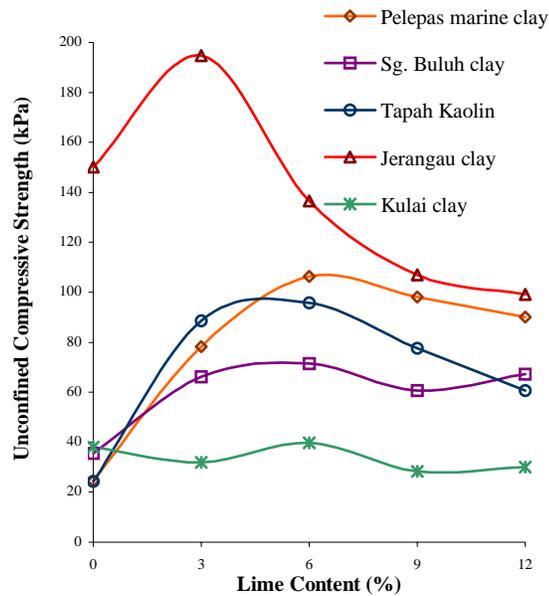


Figure 2. Compressive strength at 14 days with various additions of lime.

#### 4.6 Unconfined Compressive Strength (UCS)

Figure 3 shows the results of UCS with different curing time from 7 days to 56 days at room temperature of  $27\pm 2^{\circ}\text{C}$ . The strength of Kulai clay increases gradually at about a constant rate, during the first 7 and 28 days of curing. After 28 days of curing the increase was more rapid with a maximum of more than 200%. The Pelepas marine clay shows the highest initial increase in UCS, i.e. 3.6 times that of the untreated soil. The Sg. Buluh clay, however shows a smaller increase in strength even after 28 days of curing. It could be due to the solubility of the clay minerals at that stage, which does not encourage the reaction between lime and clay. More lime may be required to maintain the alkaline condition so as to promote pozzolanic reaction. The strength of Tapah Kaolin increases rapidly with age at a constant rate. At 56 days of curing with an optimum lime content of 6%, Tapah kaolin has developed in strength to more than 11 times higher than that of the untreated soil. The untreated Jerangau clay exhibits an average UCS of about 150 kPa. With addition of 3% lime, the stabilised Jerangau clay increases slowly at the first 7 and 14 days of curing but the increase rate became more rapid to more than 200% at 56 days of curing.

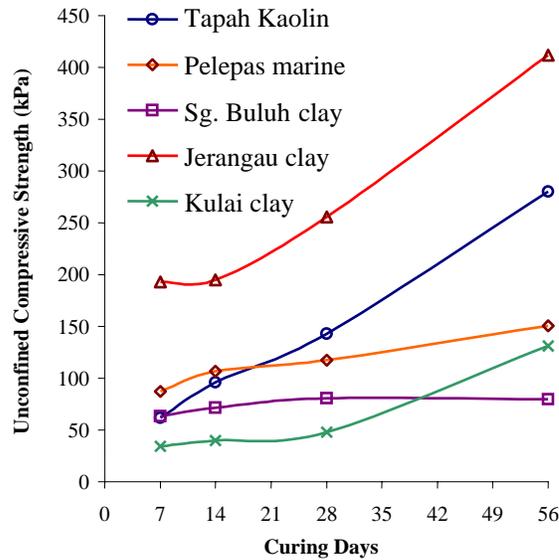


Figure 3. Unconfined compressive strength at mix design with various curing days at room temperature.

## 5. Mechanism of strength development

Soil strength development due to liming treatment was carried out using the X-ray diffraction (XRD) and scanning electron micrographs (SEM). New compounds formed due to pozzolanic reaction were identified using the XRD and SEM techniques.

### 5.1 Mineralogy of Treated and Untreated Soils

XRD investigation was conducted at 14 curing days to evaluate the minerals transformation at optimum lime content. The detail results are tabulated in Table 4. In general, minerals composition from the XRD results can be categorised as clay minerals, non-clay minerals, additive and new reaction products. Mineralogy plays an important role in establishing the character of a soil. The clay minerals found in the soil samples are kaolinite, chlorite and illite whereas the non-clay minerals are quartz, gibbsite, goethite, orthoclase, aragonite and calcite.

Table 4: Summary of minerals in the decreasing order by XRD of untreated and 14 days lime treated soils

Soil Description	Mineral		Composition
	Untreated Soil	Lime Treated Soil	
Kulai clay	Quartz	Quartz	SiO <sub>2</sub>
	Orthoclase	Orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>
	Kaolinite ★	Kaolinite ★	Al <sub>4</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>
	Gibbsite	Portlandite ❖	Ca(OH) <sub>2</sub>
	CASH	CASH *	CaAl <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> ·3H <sub>2</sub> O
	Calcite	Gibbsite	Al <sub>2</sub> (OH) <sub>6</sub>
	CSH	Calcite ❖	CaCO <sub>3</sub>
		CSH *	3CaO·2SiO <sub>2</sub> ·3H <sub>2</sub> O
Pelepas marine clay		Quartz	SiO <sub>2</sub>
		Chlorite ★	(Mg, Fe <sup>2+</sup> ) <sub>10</sub> Al <sub>2</sub> (Si, Al) <sub>8</sub> O <sub>20</sub> (OH, F) <sub>16</sub>
	Quartz	Aragonite	CaCO <sub>3</sub>
	Aragonite	Goethite	FeO·OH
	Chlorite ★	Gibbsite	Al <sub>2</sub> (OH) <sub>6</sub>
	Kaolinite ★	Kaolinite ★	Al <sub>4</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>
	Gibbsite	Portlandite ❖	Ca(OH) <sub>2</sub>
	Goethite	CAH *	3CaO·Al <sub>2</sub> O <sub>3</sub> ·Ca(OH) <sub>2</sub> ·2H <sub>2</sub> O
		Calcite ❖	CaCO <sub>3</sub>
		CSH *	3CaO·2SiO <sub>2</sub> ·3H <sub>2</sub> O
Sg. Buluh clay	Quartz	Quartz	SiO <sub>2</sub>
	Kaolinite ★	Kaolinite ★	Al <sub>4</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>
	Gibbsite	Illite ★	K <sub>2</sub> Al <sub>4</sub> Si <sub>6</sub> Al <sub>2</sub> O <sub>20</sub> (OH) <sub>4</sub>
	Illite ★	Portlandite ❖	Ca(OH) <sub>2</sub>
	Goethite	Goethite	FeO·OH
		Gibbsite	Al <sub>2</sub> (OH) <sub>6</sub>
		Calcite ❖	CaCO <sub>3</sub>
		CSH *	3CaO·2SiO <sub>2</sub> ·3H <sub>2</sub> O
Taph Kaolin	Kaolinite ★	Kaolinite ★	Al <sub>4</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>
	Gibbsite	CSH *	3CaO·2SiO <sub>2</sub> ·3H <sub>2</sub> O
	Quartz	Quartz	SiO <sub>2</sub>
		Gibbsite	Al <sub>2</sub> (OH) <sub>6</sub>
		Calcite ❖	CaCO <sub>3</sub>
		CASH *	CaAl <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> ·3H <sub>2</sub> O
Jerangau clay		Portlandite ❖	Ca(OH) <sub>2</sub>
	Quartz	Quartz	SiO <sub>2</sub>
	Orthoclase	Portlandite ❖	Ca(OH) <sub>2</sub>
	Kaolinite ★	Orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>
	Gibbsite	Goethite	FeO·OH
	Illite ★	Kaolinite ★	Al <sub>4</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>8</sub>
	Goethite	CASH *	CaAl <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> ·3H <sub>2</sub> O
		Gibbsite	Al <sub>2</sub> (OH) <sub>6</sub>
		Illite ★	K <sub>2</sub> Al <sub>4</sub> Si <sub>6</sub> Al <sub>2</sub> O <sub>20</sub> (OH) <sub>4</sub>
		Calcite ❖	CaCO <sub>3</sub>
	CSH *	3CaO·2SiO <sub>2</sub> ·3H <sub>2</sub> O	
	CAH *	3CaO·Al <sub>2</sub> O <sub>3</sub> ·Ca(OH) <sub>2</sub> ·2H <sub>2</sub> O	

Note: ★: Clay Minerals; ❖: Additive (Lime); \*: Cementitious products; and without any mark: Non-clay Minerals.

Portlandite or lime was added to the soil to form soil-lime mixtures known as calcium aluminate silicate hydrate (CASH). CASH occur under alkaline environment. The alkaline environment is essential in ensuring the pozzolanic reaction to occur as silica and alumina became soluble. ICL test has provided an

indication of how much lime is necessary to attain such environment. As the pozzolanic reaction progress, new compound known as CASH started to develop. This partially crystallize, CASH slowly converted into a well crystalline phase to form calcium silicate hydrate (CSH) and calcium aluminium hydrate (CAH). The crystallized compound of CSH and CAH hardened with age to form a permanent compound binding the soil particles thus increasing the shear strength of the stabilized soils.

### 5.2 Reasoning for Strength Development

Lime treated Kulai clay shows initial slow reactions for the first 28 days. The slow increase in strength achieved during the stabilization phase can be explained from the XRD results where CASH still remains unconverted to CSH or CAH even after 14 days of curing. Pelepas marine clay responded more quickly to strength gain due to its natural alkaline environment of the parent soil thus enhancing the dispersion process, i.e cation exchange, flocculation and agglomeration. XRD test on Sg. Buluh clay exhibited high content of quartz. The high content of quartz in Sg. Buluh clay has provided the untreated soil with higher compressive strength as compared to Tapah Kaolin and Pelepas marine clay. Quartz however does not assist in the increase of strength development but instead it acts as an obstacle from achieving a good surface bonding between lime and the clay particles. Moreover the Sg. Buluh soil was quite acidic thus causing the silicate and aluminate to be less soluble. This could results in the lack of reaction between lime and clay. Tapah Kaolin has high available kaolinite which is readily to react with lime. The increase up to more than 10 times compared to the untreated soil was achieved at 56 days of curing. Lime treated Jerangau clay was treated at the mix design of 3% of lime instead of 6% based on the optimum strength gain. This is due to the higher available portlandite in the lime treated Jerangau clay as compared to the other soils. In this study, these phenomena explain how a highest clay fraction of 44.2% in Jerangau clay were not necessarily consumed the highest lime content for stabilization purposes.

### 5.3 Scanning Electron Micrographs Observations

As shown in Figure 4, the clay lumps were being coated and bound by the silicate gel, where the process of aggregation starts to occur with a kind of spongy appearance. Aggregated particles with open type of fabric elements are very obvious. The gels cemented the particles to form aggregated crumbs. The cementation products formed were identified by XRD known as CAH and CSH. As shown in Figure 5, the soil-lime mixtures micrographs illustrate the new phase

consists of an interlocking network of needle like crystals. After curing for a year, bridges are formed between adjacent soil particles. These interlocking networks of needle like crystals have grown into the interstices to form a continuous network.

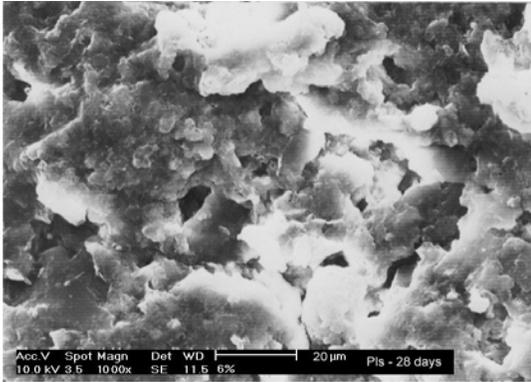


Figure 4. SEM of 6% lime treated Pelepas marine clay after 28 days of curing (20µm).

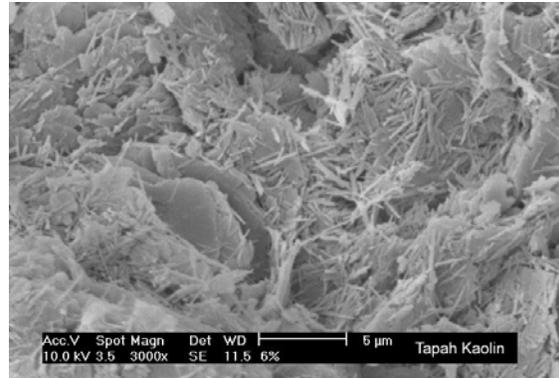


Figure 5. SEM of 6% lime treated Tapah Kaolin after one year of curing (5µm).

## 6. Conclusions

The optimum lime contents for stabilising the tested Malaysian cohesive soils range between 3.0 and 6.0%. This was achieved through a mix design long-term stabilisation process based on the gained compressive strength. The strong alkaline conditions with pH of 12.4 were able to release silica and alumina from the clay mineral and eventually to react with lime to form new cementitious products known as CASH. CASH was then crystallised to form CSH and CAH. Clay minerals such as kaolinite, chlorite and illite found in the untreated soils play an important role in forming the mineralogical characteristic of the soils. Tapah Kaolin, the only soil with the clay mineral of kaolinite with 100% relative intensity produces new well-crystallised compounds, CSH with a high relative intensity. Evidence from the XRD analysis has shown that the new phase consists of new cementation products namely hydrate calcium silicate or calcium aluminates. The success of the treatment process is highly dependent on the available lime content, curing time, soil type, soil pH and clay minerals.

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