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SETTLEMENT BEHAVIOUR OF A CEMENT-STABILISED MALAYSIAN CLAY

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ABSTRACT

Soft clay soils often cause difficulties in construction operation with their low strength and low stiffness nature. However the engineering properties of these clay soils can be enhanced by adding ordinary Portland cement (OPC) for modification or stabilisation purposes. This paper describes the application of the cement stabilisation technique for improving the engineering properties of a soft Malaysian clay. The objectives of this study are two-fold: firstly, to study the settlement behaviour of the cement-treated clay using standard oedometers; and secondly, to explore the equal strain approach for predicting the settlement pattern of a stabilised columnar system for the clay. The quantities of cement added to the clay were 5 %, 10 % and 20 % by dry weight of the clay. The specimens were next cured in dry condition for 7, 14 and 28 days respectively to allow for investigation of the curing effect. The oedometer test results showed that cement is effective in enhancing the settlement resistance of the originally weak clay soil, and interestingly, compressibility of the clay was not markedly improved for specimens left to cure for longer periods than 7 days. In addition, settlement prediction of the stabilised columnar system using the equal strain approach showed that a columnar inclusion test in the oedometer can simulate the compressibility behaviour of a single column system with sufficient accuracy.

INTRODUCTION

The construction of large and small defences against water and other hostile invaders, as well as infrastructure works for residential areas and transport, has over the centuries been dominated by the specific problems of structures situated on a subsoil of low bearing capacity and high compressibility (CUR C68/2-07, 1991). Highly compressible soil is generally also of low bearing capacity, and is commonly referred to as ‘soft’, which means that it has poor resistance to deformation and has low bearing capacity (CUR C68/4-04, 1991). Besides, soft clay deposits are widespread and cover many coastal regions of the world, such as in Japan, Eastern Canada, Norway, Sweden, India and South East Asian countries (Nagaraj and Miura, 2001).

To control and solve the low strength and stiffness problems, suitable ground improvement techniques are necessary for these problematic soils to ensure stability and to limit the ground deformation. Cement stabilisation is one of the alternatives. The conventional cement stabilisation method was used initially for surface treatment, but the use of cement has now been extended to greater depths, where cement columns are installed to act as soil reinforcement, i.e. deep soil-cement mixing.

Dry Jet Mixing (DJM) is a soil improvement technique that pneumatically delivers powdered cement into the ground and mixes it with in situ soils to form a soil-cement matrix or column. The chemical reactions between water in the soils and the cement powder would produce ‘cementation’, which increases the strength and reduces the compressibility of the originally soft soil. Due to its many advantages, DJM has attracted increasing attention compared to other in situ soil stabilisation methods since its early development in Sweden and Japan in the 1970’s. Today the cement stabilisation method is used worldwide for improving soft soils as pre-treatment to construction works (Bruce et al, 1999).

PROJECT BACKGROUND

The soft soil used in this study was retrieved from the RECESS’s (Research Centre for Soft Soils) test site at Universiti Tun Hussein Onn Malaysia, located in the southern state of Johor in Peninsular Malaysia. According to Laidin (2004), the soft clay layer in the University’s grounds extends to a depth of 40 m. It is therefore not deemed practical to be removed and replaced for construction works as this process is expensive and time-consuming. The soft clay has high moisture content, low shear strength, low permeability, high compressibility, shrinks when dried and expands when wetted (Chan 2006). Problem arises when structures are built on these soils, where under large superimposed load, significant settlements can occur if the soil is not being improved first.

Stabilisation with cement is one of the soil treatment methods that can be applied to improve soil’s plasticity and workability.

In this study, oedometer tests were conducted to study the settlement characteristics or 1-D compressibility of the stabilised material. Based on homogeneuous specimens test results and data from further columnar inclusion tests, settlement prediction of the stabilised columnar system was also made using the equal strain approach.

Fig. 1. The RECESS's test site and clay sample retrieval.

SOFT SOIL STABILISATION

The addition of small amounts of cement, up to 2 %, modifies the properties of soil, while large quantities have more significant effect. In fact cement may range from 3 - 16 % by dry weight of soil, depending on the type of soil and properties required. Generally as the clay content of soil increases, so does the quantity of cement required (Bell, 1993). When the mechanical stability of a soil cannot be obtained by combining materials, it may be advisable to order stabilisation by the addition of cement, lime, bituminous material or other special additives.

Soil-Cement Modification

Modification occurs when calcium ions liberated from the cement during hydration and hydrolysis occupy the positions of exchangeable ions on the surface of the clay minerals. Therefore, soil modifications are usually carried out to increase strength and stability, to control deformability and to reduce plasticity.

Soil-Cement Stabilisation

Soil stabilisation occurs when cement is added to a reactive soil to generate long-term strength gain through cement reaction. This reaction produces stable calcium silicate hydrates and calcium aluminate hydrates as the calcium from the cement reacts with the aluminates and silicates solubilized from the clay. As a result, cement treatment usually produces high and long lasting strength gains.

The improvement in engineering properties of cement-treated soils is believed to be due mainly to the hardening of cement in the presence of moisture and extension of curing period. Different cement contents and curing period render different reactions for cement-treated soils. Soil cement is the reaction product of an intimate mixture of pulverized soil and measured amounts of Portland cement and water compacted to high density.

Differences between Modification and Stabilisation

Modification	Stabilisation
A small alteration, adjustment or settlement limitation.	To make stable or increase stiffness.
Low additive content to make soil slightly stiffer.	High additive content to achieve higher stiffness.

METHODOLOGY

All laboratory tests are conducted in accordance with standard procedures as given in BS 1377: Part 2: 1990. Basic tests were also carried out to determine physical properties of the clay soil.

Preparation of Specimens

Disturbed bulk samples of clay soil was retrieved from the RECESS test site at about 1.5 m depth (Fig. 1). The sample was then wrapped in plastic bags and immediately transported to the laboratory for storage. Index properties of the clay are given in Table 1.

For preparing the test specimens, the clay was first remoulded to ensure uniform distribution of the pore water. Predetermined amounts of cement based on dry weight of the clay (i.e. 5, 10 and 20 %) were then added to the clay and thoroughly mixed by hand. The soil-cement mixture was next compacted in the oedometer ring. Two types of specimens were prepared in this study: homogeneous specimens and columnar inclusion specimens (Fig. 2).

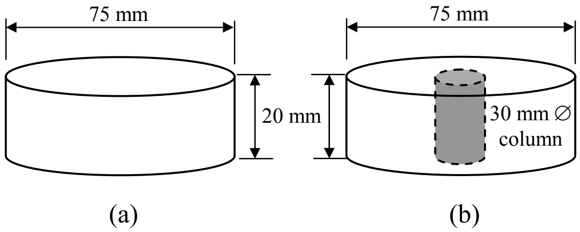


Fig. 2. a. Homogeneous specimen.
b. Columnar inclusion specimen.

The specimens were next dry cured for 7, 14 and 28 days respectively on raised platforms in a tighly sealed polystyrene box at 20°C. A mild bleach solution was added in the storage box to prevent fungal growth on the specimens.

Table 1. Index properties of the clay

Water Content (%)	LL (%)	PL (%)	G_s	Group Symbol
83.2	83.9	32.3	2.63	CH

A total of 14 specimens were prepared and tested in this study: 12 homogeneous specimens and 2 columnar inclusion ones. A summary of the test specimens is given in Table 2.

Table 2. Test specimens

Specimen	Cement Content (%)	Curing Period (days)
S0_7d	0	7
S5_7d	5	7
S10_7d	10	7
S20_7d	20	7
S0_14d	0	14
S5_14d	5	14
S10_14d	10	14
S20_14d	20	14
S0_28d	0	28
S5_28d	5	28
S10_28d	10	28
S20_28d	20	28
COL5_7d	0	7
COL10_7d	10	7

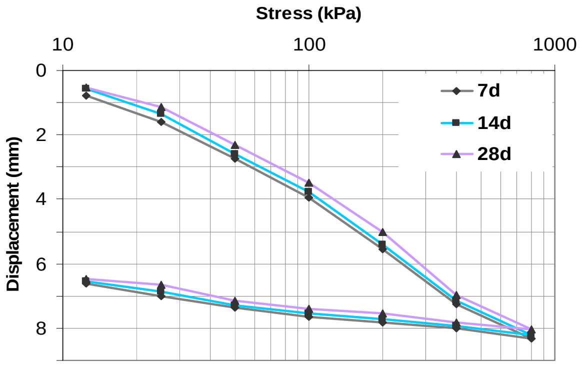
Oedometer Tests

The oedoemter tests were conducted in accordance with the BS 1377 (1990). The loading sequence started with 12.5 kPa, followed by increments in the multiple of 2 (i.e. 25 kPa, 50 kPa, 100 kPa, etc.) to the maximum of 800 kPa over 7 days. The specimens were then unloaded following the same but reversed sequence before the tests were terminated.

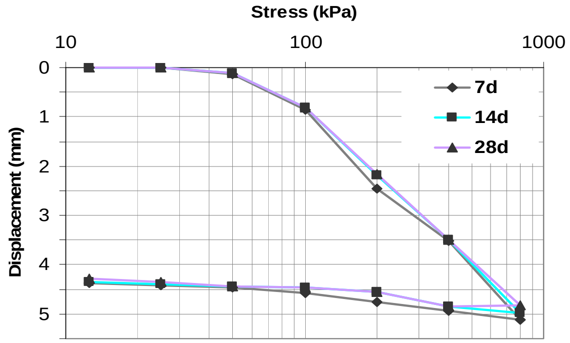
RESULTS AND DISCUSSIONS

Homogeneous Specimens

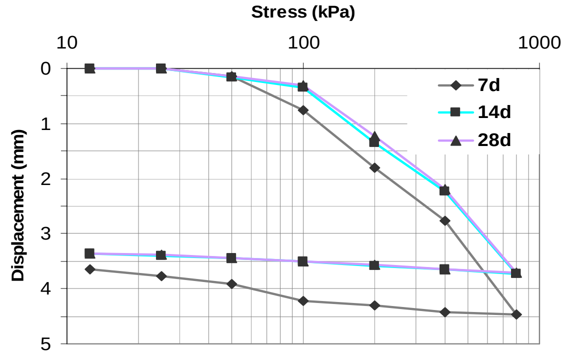
Compression curves of all specimens, grouped according to the cement content, are shown in Figs. 3a – 3d. The unstabilised specimens (i.e. 0 % cement content) demonstrated marginally improved compressibility despite the effect of curing (Fig. 3a).



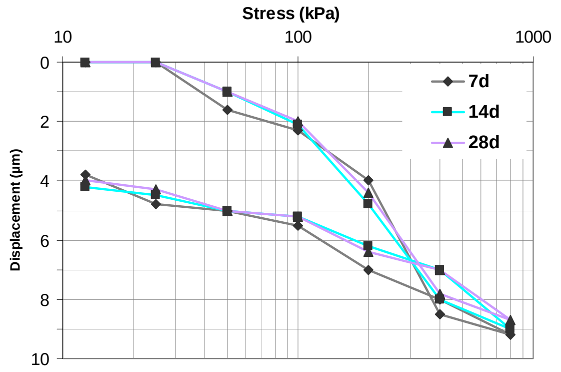
a. 0 % cement content.



b. 5 % cement content.



c. 10 % cement content.

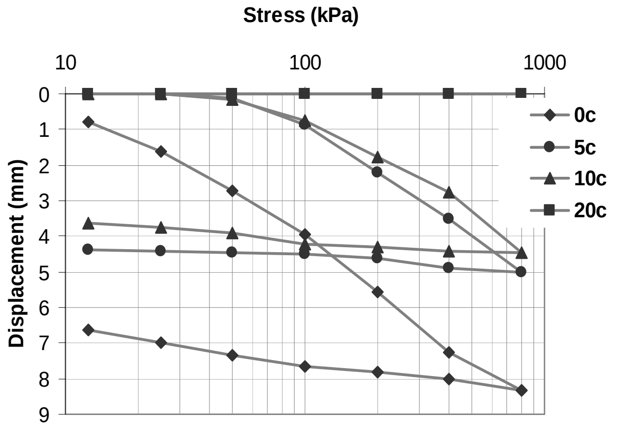


d. 20 % cement content.

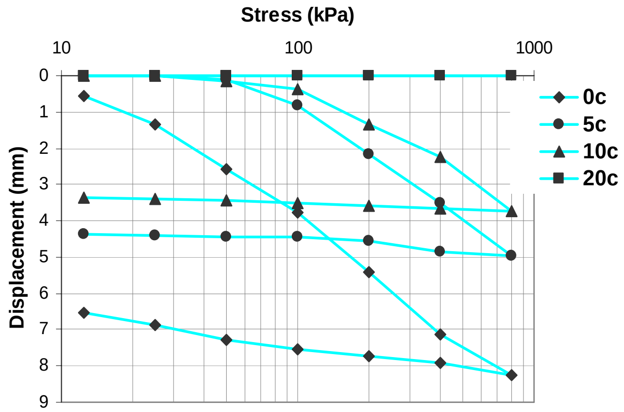
Fig. 3. Compression curves of homogeneous specimens- grouped by cement content.

The slight reduction of settlement was mainly attributed to aging, as commonly observed in unstabilised clays (Bjerrum and Lo 1963, Schmertmann 1991).

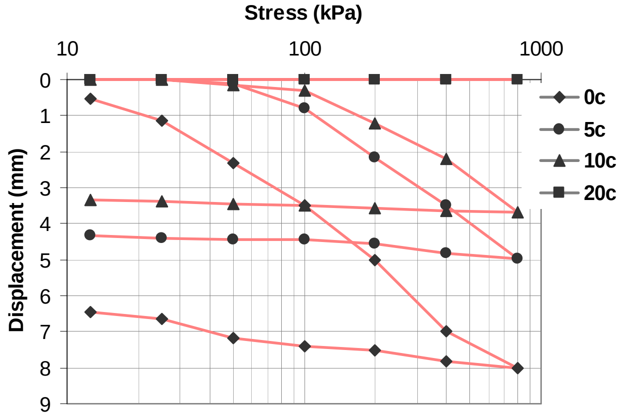
Figs. 3b, 3c and 3d illustrate the compression patterns of homogeneous specimens with 5, 10 and 20 % cement contents respectively. It is apparent that curing beyond 7 days had insignificant effect on the stiffness improvement, where the settlements under each applied stress and yield stresses (pre-consolidation stresses, σ_y') remained largely unchanged compared to those of the 7-day ones. This is similar to the observations reported by Chan (2007) on oedometer tests with stabilised kaolin and Swedish clay specimens. Prolonged curing period seemed to be unecessary to achieve higher stiffness, as opposed to findings on stabilised Bangkok clay by Uddin et al. (1999), that a minimum of 1 month curing is required to attain meaningful improvement. Nevertheless the quantity of cement added is an important determinant factor, along with the initial water content of the soil to be stabilised.



a. 7 days curing.



b. 14 days curing.



c. 28 days curing.

Fig. 4. Compression curves of homogeneous specimens- grouped by curing period.

Analysis of the compression curves in terms of effectiveness in settlement control revealed that higher cement content resulted in less settlement in the specimens (Figs. 4a – 4c). Note that the settlemens for the 20 % cement content specimens were quoted in µm (10^{-6} m). While it is acknowledged that external displacement measurements on a stiff specimen could be compounded by apparatus and experimental errors, consistency of the settlement data recorded for the 7, 14 and 28-day 20 % cement specimens indicated that the errors had either been systematic or negligible. On average, 5 % cement reduced the total settlement by 40 %, 10 % cement brought the settlement down by 48 % and 20 % cement produced a reduction in settlement by almost 100 %.

Columnar Inclusion Specimens

Columnar inclusion test was conducted for specimens with 5 % and 10 % cement content, where the stabilised column with a diameter of 30 mm was formed within the unstabilised soil mass in the oedometer ring (Fig. 2b). The surface area of the column (a) is 0.16 of the total surface area (A). Considering that curing of 7 days was sufficient, the columnar inclusion specimens were both cured for 7 days prior to testing.

The compression curves of the columnar inclusion specimens are plotted with the homogeneous ones for convenience of comparisons (Fig. 5). As can be readily perceived, the columnar specimen curve lies between those of the homogeneous specimens, i.e. unstabilised clay and stabilised ones.

Settlement Prediction

Taking an equal strain assumption (Baker 2000), and based on the surface areas of column and surrounding unstabilised clay, values of force on each component (i.e. P_{col} and P_{soil}) were calculated by multiplying the appropriate effective vertical stress, σ'_{col} or σ'_{soil}, with the respective surface area. Note that σ' for the column and soil at a common strain are significantly different (Table 3). The values of σ'_{pred} was next obtained by dividing the total load, ($P_{col} + P_{soil}$), by the total surface area of the composite sample. By comparing the last two columns of the table, the difference between σ'_{pred} and σ'_{test} can be assessed. Following is a summary of the calculations involved:

$$\sigma'_{soil} = P_{soil} / (A - a) \qquad (1)$$

$$\sigma'_{col} = P_{col} / a \qquad (2)$$

$$\sigma'_{pred} = (P_{soil} + P_{col}) / A \qquad (3)$$

Table 3a. Settlement prediction for 5 % cement column

Strain (%)	σ'_{soil} (kPa)	σ'_{col} (kPa)	σ'_{test} (kPa)	σ'_{pred} (kPa)
5	15	110	13	30
10	32	185	39	62
15	60	300	65	99
25	170	800	184	271

Table 3b. Settlement prediction for 10 % cement column

Strain (%)	σ'_{soil} (kPa)	σ'_{col} (kPa)	σ'_{test} (kPa)	σ'_{pred} (kPa)
5	15	125	40	33
10	32	235	80	67
15	60	440	145	121
22.5	135	800	275	242

The predicted curves on Fig. 5 were in fairly good agreement with the columnar inclusion tests, though the agreement was better for the 10 % cement columnar system. It appears that a reasonable prediction of the compression curve of a single column system can be derived from the oedometer test data of both the unstabilised clay and cemented specimens. However, it was unlikely that the soft unstabilised clay surrounding the column could have completely prevented radial expansion of the column in the centre and deforming only in the vertical direction. This is further discussed in the next section.

Radial Expansion of Column

Table 4. Changes in column diameter

Cement content of column	D_0 (mm)	D_f (mm)	ΔD (%)
5 %	29.8	33.0	10.74
10 %	29.8	32.0	7.38
20 %	29.8	30.4	2.01

D_o = pre-test diameter
D_f = post-test diameter

Radial expansion of the columnar inclusion was expected as the soft clay surrounding the column was too weak to restrain the stiffer column from expanding. Changes in the column diameter are given in Table 4. The pre- and post- test diameter difference (ΔD) was most significant for the lowest cement content specimen.

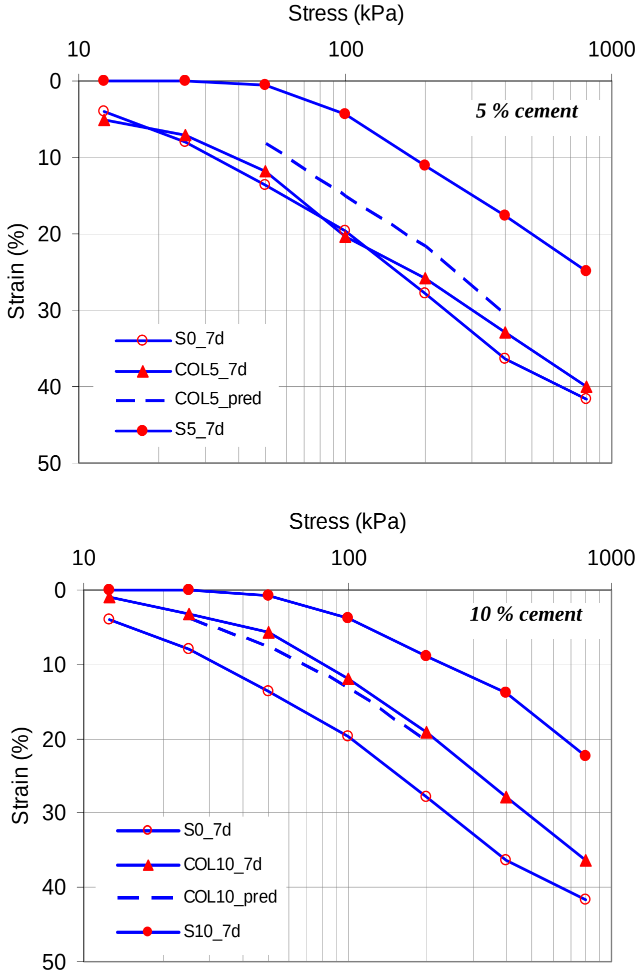


Fig. 5. Compression curves of columnar inclusion specimens.

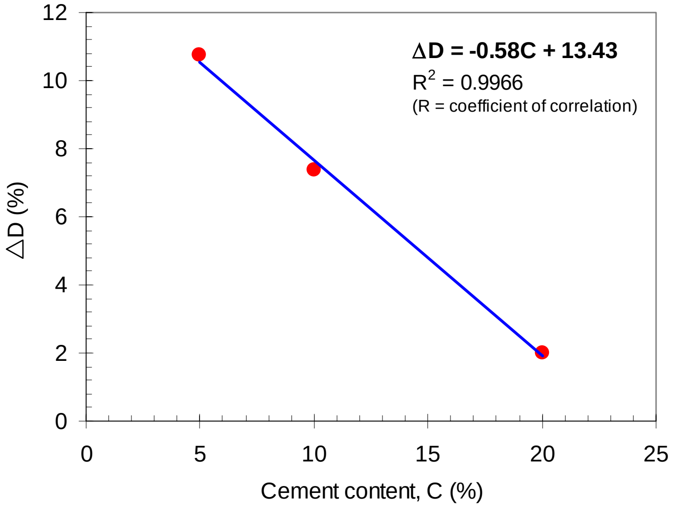


Fig. 6. ΔD – cement content (C).

Fig. 6 is a plot of ΔD against cement content in the column. The relationship was found to be linear with a gradient of approximately -0.6. This goes on to show that radial expansion of a cement-stabilised column is inversely proportional to the cement content.

CONCLUSIONS

Cement stabilisation was proven to be an effective means of improving the compressibility of the soft clay found in abundance in the southern state of Johor, Malaysia. As little as 10 % cement could significantly reduce the total settlement under loading by nearly half, suggesting that excessive amounts of stabiliser is not necessary to produce an effective stabilised columnar system. Besides, curing period exceeding 7 days was found to be of little benefit to the improved stiffness of the stabilised clay. Final endeavour in the study to back analyze the settlements using the equal strain approach showed that standard oedometer test on homogeneous specimens could provide sufficiently accurate results for making predictions on the settlement pattern of a single columnar system.

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