Preliminary Study of S-Wave Velocity and Unconfined Compressive Strength of Cement-Palf Stabilised Kaolin

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Abstract

Clays are notoriously well known for giving rise to myriad problems and difficulties in construction due to excessive settlement and limited strength. Hence, there is a need to pre-treat the soils prior to construction, such as improving the engineering properties via the stabilisation technique, before additional load can be applied on it. In soil stabilisation, cement is commonly used as a stabilizing agent, to simultaneously increase the strength and stiffness of the originally weak, soft material. However cement is relatively expensive and potentially harmful to the environment when admixed with soils. The need for alternative stabilizing agents which could reduce the use of cement is therefore apparent. In this study, natural fibres were retrieved from pineapple leaves, an agricultural waste product typical of Johor. Next pre-determined quantities of pineapple leaf fibres (PALF) were added to an artificial clay, kaolin, together with cement. The mixture was formed into specimens of 38 mm diameter and 76 mm high, cured in dry condition before being subjected to the s-wave velocity and unconfined strength measurements. A range of curing period was introduced to examine the effect of time on the performance of the stabilised specimens too. It was found that the fibres function as a form of reinforcement to the soil. Also, the test data revealed that PALF alone makes negligible contribution to the improved properties, where cement is necessary to act as a binder to strengthen the soil matrix. Nevertheless the potential of using PALF as an additive to cement in soft soil stabilisation is promising, though further work is necessary to better understand the stabilised material and its long term performance.

Keywords: cement, kaolin, PALF, soil stabilisation

1. INTRODUCTION

As a result of extensive urbanisation and industrialisation, the scales of design and construction of infrastructure on natural soft ground have increased tremendously. Nevertheless, the low strength and highly compressible soft soil are susceptible to large settlements, making pretreatment of the soils, such as stabilisation, necessary [1].

In their experiments with a range of cement percentage addition to a soil sample, Consoli *et al.* (2007)[2] found that the effect of cement content on the unconfined compressive strength of sandy soil was more significant with higher cement quantities, where 7 % of cement addition resulted in approximately 3.2 MPa peak strength. Ibrahim (2007)[3] experimented with soft marine clay stabilisation and discovered that cement-PALF addition could yield significant strength improvement. It was reported that the strength was increased from below 10 kPa to 159 kPa with the addition of 2.5 % PALF and 10 % cement. Besides, the utilisation of PALF in soil stabilisation could help reduce solid wastes disposal through open burning, hence contributing to environmental pollution control too. Besides, Al-Akhras (2003)[4] found that the peak unconfined compressive strength and stiffness of a fibre reinforced clayey soil (without cement) were 240 kPa and 8 GPa respectively at fibre contents of 5 %. That shows a 50 % improvement from the existing strength of 160 kPa and 100 % gain in stiffness from 4 GPa as measured in the original soil specimen.

In terms of s-wave velocity measurements in stabilised soils, based on Qiu *et al.* (2008)[5] , consideration of effective density will not be important for clays, unless the shear wave frequency is very high, i.e. >10 kHz. Puppala *et al.* (2006)[6] reported that cement treated clays showed considerable increase in small strain stiffness properties, from 0-100 MPa to 200-500 MPa, compared with the control specimens (i.e. untreated clays). According to Heineck *et al.* (2005)[7], at very small shear strains (measured with bender elements), polypropylene fibre reinforcement does not influence the stiffness of the soils, but the effect of the fibre addition can be pronounced at very large shear strains with significant horizontal displacements observed on the test specimens.

In the present study, an attempt was made to improve the engineering properties of artificial clay, i.e. kaolin, by using cement admixed with an agricultural waste material, i.e. pineapple leaf fibre (PALF). The main objective of this study is to identify and establish the correlations between the two main mechanical properties of the cement-PALF stabilised specimen, i.e. shear wave velocity (v_s) and unconfined compressive strength (q_u).

2. MATERIALS AND METHODS

2.1 Raw Materials

Three main raw materials were used in preparing the stabilised soil specimens, namely kaolin as the base clay, ordinary Portland cement (OPC) and PALF as the stabilizing agents. The kaolin was supplied by Kaolin (M) Sdn. Bhd.[8] and the OPC was procured from Holcim (M) Company[9], where both came in powder form. The properties of kaolin and chemical composition of cement are given in Table 1 and 2.

PALF, on the other hand, was extracted from the pineapple leaves (collected from a local plantation in Parit Botak, Johor) using the ‘bowl-scraping’ method (Fig. 1). The method was found to be manually feasible, easy and time-saving in extracting the fibres from raw pineapple leaves. There was no machinery required and therefore gave the method an economical edge. The pineapple leaf was first scraped by using the edge of a small bowl. Next the loosened fibres were peeled off the pineapple leaf by hand. The extracted fibres were then soaked in water briefly to remove any remaining sap. Finally the water was drained and the fibres were left to air-dry for 24 hours. The processed fibres were finally cut into 10 mm lengths so as to ensure uniformity and consistency of in preparing the test specimens.

Fig. 1: The 'bowl-scraping' method for extracting PALF

2.2 Experimental Work

The physical and mechanical properties tests were carried out based on procedures given in BS 1377: 1990[10], the technical manuals of GDS Bender Element Test System (for shear wave velocity measurement) and the Geocomp LoadTrac II Test System (for unconfined compressive strength measurement).

A fixed amount of water (i.e. 35 %) was added to all specimens, as derived from the standard compaction test carried out on kaolin. Details of test specimens prepared for this study are shown in Table 3.

Pre-determined amounts of kaolin powder, water, cement and PALF were mixed thoroughly using a conventional food mixer, following the steps described by Chan (2006)[11]. The quantities of additives were calculated based on dry weight of the soil, W_s. As can be seen in Table 3, the percentages of cement and PALF were low for a couple of reasons. The cement percentages were kept below 10 % to avoid producing specimens which were too hard and stiff, and deviating from the stabilised soil principles of having semi-rigid stabilised material interacting with the surrounding unstabilised soils. Of course, it would also have required a different test setup should such stiff specimens were to be tested, where the standard soil testing equipment would not have been able to cater for the high strength and stiffness measurements. The low PALF contents, on the other hand, were primarily due to the huge volume of fibres even at small quantities because of the fibre's low density.

The soil mixture was then transferred to a standard 76 mm x 38 mm cylindrical split mould in three layers. Each layer was manually compacted with of 10 blows of rubber pestle on a 76 mm metal rod. The final layer was compacted by using a hydraulic compression machine at 2 MPa. The compacted specimen was then extruded from the mould, wrapped with cling film, and stored in an airtight container for different curing periods prior to testing.

Table 1: Properties of kaolin

Properties	Characteristics
Moisture content	<7%
Specific gravity	2.6
Liquid limit	60.5%
Plastic limit	42.5%
Plastic index	18.0%
Optimum moisture content	35%
Maximum dry density	1350 kg/m^3
Loss on ignition	10.5-13.0 %

Table 2: Chemical composition of cement

Chemical Component	Amount (%)
SiO_2	21.00
Al_2O_3	5.50
Fe_2O_3	3.30
CaO	65.60
MgO	1.40
SO_3	2.70
C_3S	60.00
C_2S	15.00
C_3A	8.05
C_4AF	9.76
Ignition loss (LOI)	1.40

Table 3: Details of test specimens

Specimen	PALF, P (%)	Cement, C (%)
P0C0	0	0
P0C3	0	3
P0C6	0	6
P0.25C0	0.25	0
P0.25C3	0.25	3
P0.25C6	0.25	6
P0.5C0	0.50	0
P0.5C3	0.50	3
P0.5C6	0.50	6
P0.75C0	0.75	0
P0.75C3	0.75	3
P0.75C6	0.75	6

2.2.1 S-wave Velocity Measurement

S-wave velocity measurement in soils to determine the shear stiffness is gaining popularity among geotechnical researchers as a non-destructive test. It is essentially quick and simple to perform, and can be repeated on the same specimen over a period of time, eliminating the inconsistencies due to the inherent properties of the different test specimens.

The s-wave velocity was measured using the GDS Bender Element (BE) Test System, which uses a pair of piezoelectric transducers, i.e. a transmitter and a receiver, to send and receive s-waves through a soil specimen. Pre-made slots on each end of the specimen were filled with plasticine as a coupling agent to ensure good contact between the BE and the specimen. This was to avoid poor contact between the two which could result in poor quality signals for interpretation.

With the travel distance between the tips of bender elements on both ends (L), as well as the travel time (t) known (taken as the peak-to-peak time lapse between the transmitted and received signals), the s-wave velocity (v_s) was simply computed as $v_s = L/t$. Higher velocities indicate stiffer materials, as v_s for a homogeneous and isotropic material under plane wave propagation assumption is related to the small strain shear modulus, $G_o = \rho v_s^2$, where ρ is the bulk density of the material through which the wave travels [12].

2.2.2 Unconfined Compressive Strength (UCS) Test

The UCS test was conducted with the automated Geocomp LoadTrac II Test System. As shown in many past research work, the UCS test has been carried out successfully for reliable strength measurements of stabilised soils, making it a good choice as a test as well as for data comparison purposes. The specimen was placed on the platen and loaded at a constant strain rate of 1 mm per minute. The load and displacement data during test were recorded automatically by the manufacturer's PC-based programme.

Note that s-wave velocity of the specimens was monitored regularly from the 7th. to 56th. day, while the UCS tests were carried out on the 7th and 28th days old specimens only. This was primarily due to the constraint of limited specimens for the destructive compression tests.

3. RESULTS AND DISCUSSIONS

3.1 Water Content, w

Fig. 2 shows the effect of the cement on the water content of the stabilised specimens. It can be readily observed that the water content of the stabilised clay decreased with higher cement dosage and longer curing period. Initial water content of approximately 35 % dropped to 15-34 % after curing, indicating the on-going cement hydration process which significantly dried up the wet soil.

Comparing specimen P0C6 and P0.75C6 at 7 days curing, the latter had slightly lower water content, indicative of the moisture-absorbent nature of the fibres (Fig. 2). This could be a benefit in reducing the initial water content of a wet soil specimen, hence improving the overall strength and stiffness. Specimen P0C6 registered a further reduction in water content after 28 days of curing, from 30 % at 7 days to 15 % at 28 days. Interestingly, the water absorption observed in specimen P0.75C6 seemed to have continued throughout the 3 weeks lapse, showing an increment of approximately 3 % from the 7th. day old water content of 28 %.

Fig. 3 summarizes the final water content and q_u of all the specimens. Higher percentage of water content resulted in lower q_u values regardless of the age of the specimens, as only to be expected of a wetter and softer material. The plot does, however, highlight the fact that the strength of a cement-PALF stabilised specimen is hardly predictable by just measuring the water content alone. Clustering of the 7- and 28-day old stabilised specimens on the same range of water content in Fig. 3 clearly shows how misleading such prediction could be.

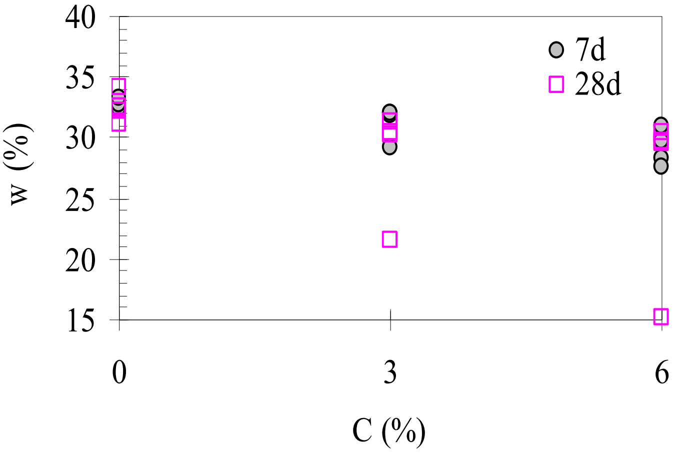


Fig. 2: Water content – cement content

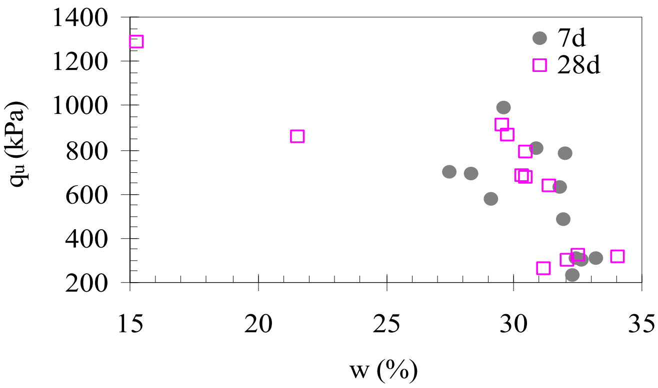


Fig. 3: q_u (kPa) – w (%).

3.2 Atterberg Limits

There were no significant changes in the liquid limit of the specimens, i.e. 55-66 %, despite the addition of fibres in the specimens. Referring to Table 1, the liquid limit for kaolin was 60.5 %. After treatment with 6 % cement, the liquid limit decreased to 55.2 %, a marginal change showing that cement did contribute to a slight decrease in the liquid limit.

On the contrary, there was a large change in the plastic limit, which ranged between 20.8 and 45.7 %, with a significant difference of 24.9 % between the highest and lowest values. These inconsistencies were mainly attributed to experimental limitations, where inclusion of the fibres made it almost impossible to roll the stabilised material into strips of 3 mm in diameter without breakage.

3.3 S-wave Velocity, v_s

Generally, v_s increased with longer curing time and higher cement dosage (Fig. 4). In addition, the received signals grew stronger with greater amplitudes, indicating the stiffening effect cement-PALF had on the stabilized specimens. All the specimens stabilised with 6 % of cement achieved v_s well above 290 m/s compared to the specimens without cement addition, i.e. P0C0 and P0.75C0. Cement was apparently the primary bonding agent in the stabilised soil mixture, where cement hydration formed a stiffer soil matrix in the stabilised specimens. Also, note that none of the specimens with fibres added achieved v_s as high as specimen P0C6, suggesting the retarding effect PALF actually has on cement stabilisation.

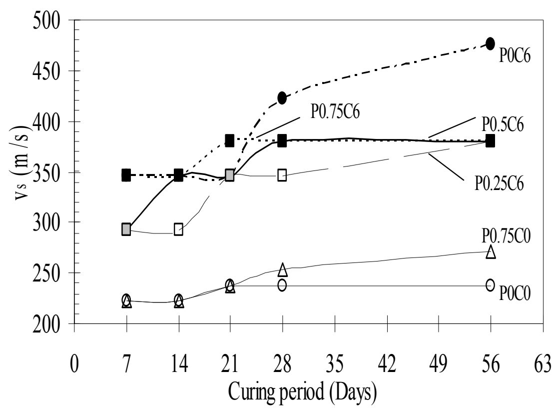


Fig. 4: S-wave velocity-curing period.

The v_s values levelled off after 28 days, indicating the completion of the cement hydration process. Apart from specimen P0C6 which clearly underwent pozzolanic reaction beyond 28 days with rising v_s, the negligible increase in v_s for the other specimens was most likely due to aging, a time-dependent process where soil particles rearranged themselves into a denser pack.

3.4 Unconfined Compressive Strength, q_u

From the plots shown in Fig. 5, it can be seen that specimens with higher cement content produced higher peak strength. Similar results have been reported by Anagnostopoulus *et al.* (2003)[13] and Consoli *et al.* (2007)[2], where cement was found to significantly improve the soil's strength.

Comparatively, in Fig. 5, q_u of the control specimen (i.e. P0C0) remained largely unchanged, even with prolonged curing. As for the specimens stabilised with PALF without cement, the plot lies just above that of the control specimen, showing that PALF alone does not contribute much to the strength improvement of clay.

Nevertheless, the fibres helped to hold the specimen together during compression, especially nearing failure. Specimen P0C6 registered the highest strength, i.e. ≈ 1300 kPa, while specimen P0.75C6 had the lowest strength if compared with other specimens with the same cement content, i.e. specimens P0.25C6 and P0.5C6. This may be caused by the fibres absorbing surrounding water and induced dryness within the specimen, hence making it brittle and less susceptible to compressive load.

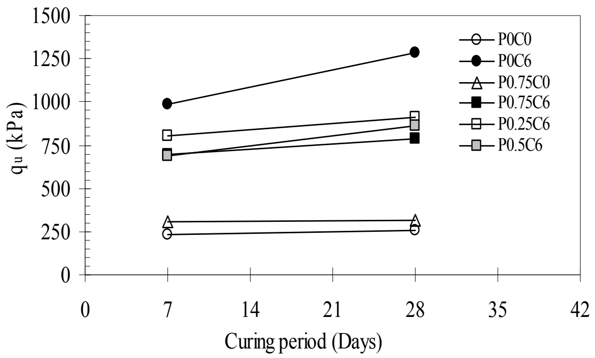


Fig. 5: Unconfined compressive strength – curing period.

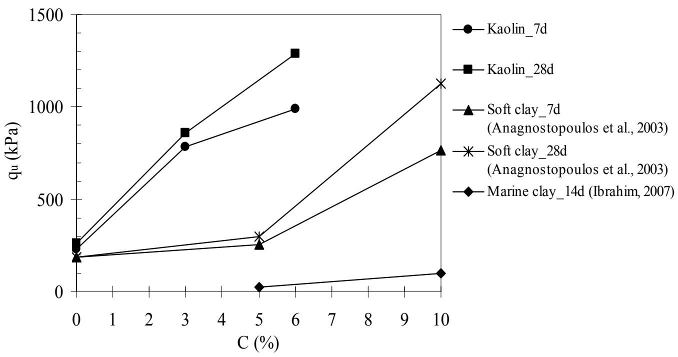


Fig. 6: Comparison of q_u for cement treated soils

Also, the plots for the specimens with cement-PALF addition (i.e. P0.75C6, P0.5C6 and P0.25C6) seem to have similar strength gain pattern, though the specimen with the least fibre content displays a slightly higher q_u. This is suggestive of the detrimental effect excessive fibres could have on stabilised soils, caused by internal dehydration and segregation of the soil matrix.

A comparison was made the current data and those from previous researches (Fig. 6), where cement was used as the main additive to stabilize different types of soft soil, including kaolin, marine clay and a highly compressible clay. The stabilised kaolin clay was found to have the highest strength compared to others. By examining the liquid limit of the soils, it was not difficult to see that kaolin, with a liquid limit of about 60 %, required more water to reach the liquid state, in comparison with, say, 44 % liquid limit of the highly compressible clay.

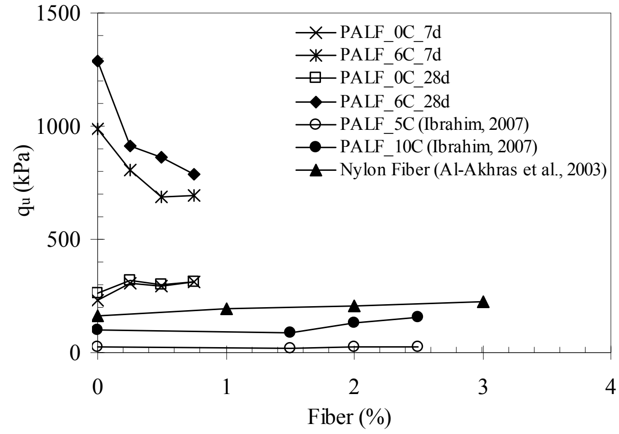
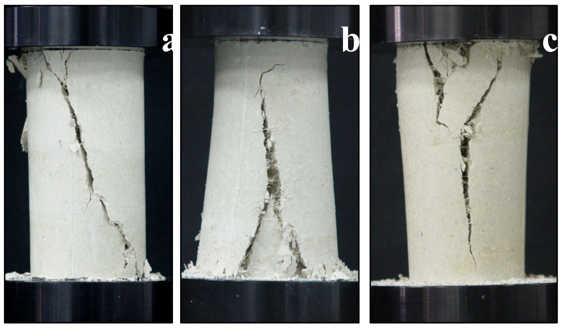


Fig. 7: Comparison of q_u for fibre-treated soils



P0.25C3 P0.75C6 P0.75C0

Fig. 8: Typical failure modes of UCS test specimens

The effect of fibre content on q_u was also examined (Fig. 7). The addition of fibre without cement increased q_u by not more than 40 kPa. Coincidently, Ibrahim (2007)[3] also found that there was negligible increase in q_u when cement was omitted. On the other hand, q_u decreased with increased PALF content when cement was added, most probably caused by the retarding action of the PALF on the pozzolanic reactions and consequently on the overall strength of the stabilised soil matrix. Besides, the high water absorption of PALF could have entrapped excess water in the stabilised specimen and hence affecting the strength, as discussed in section 3.1.

Some typical failure modes of the stabilised specimens are shown in Fig. 8. For the specimen with the least fibre content (Fig. 8a), a distinct shear failure plane was observed inclining at approximately 45^o to the horizontal axis. Fig. 8b shows a highly cemented specimen with high fibre content. The rupture appeared at the lower middle part of the specimen but the fibres obviously held the broken parts together, keeping the specimen in one piece. The failure mode in Fig. 8c gave further evidence that the fibres acted as reinforcement to prevent breakage of the specimen. In spite of a large vertical crack running down the specimen, it has remained largely intact due to the binding effect of the fibres.

3.5 Correlations between q_u and v_s

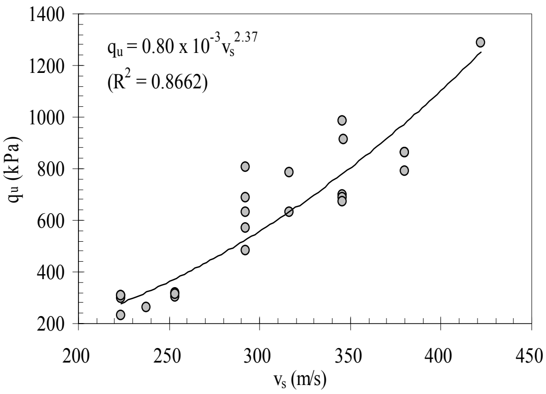


Fig. 9: q_u-v_s

By plotting the corresponding q_u and v_s values in Fig. 9, a power law regression line can be drawn through the data points with a correlation factor of almost 90 % (i.e. 90 % of the data points fit the equation derived). As the specimens were tested in pairs, the repeatability and consistency of the test specimens as well as test procedures can be considered verified to a certain degree. If discrepancies were encountered but unaccounted for, it would have been a systematic error observed in entire the data series and not affecting the general pattern or trend presented by the data.

This goes on to suggest that the non-destructive s-wave velocity measurement can be used to estimate the unconfined compressive strength of cement-fibre stabilised soils. Such correlation charts could serve as quick, convenient reference without having to prepare numerous specimens for the compression tests.

4.0 CONCLUSIONS

The conclusions drawn from this preliminary study of cement-PALF stabilised clay are as follows:

- Cement admixed with PALF can effectively strengthen and stiffen an originally soft clay, as illustrated by the artificial clay of kaolin.
- PALF alone makes little contribution to strengthen the clay, where cement is required to act as the bonding agent. There was inconsistency in the plastic limit results, with large variation ranging from 20.8 % to 45.7 %. The inclusion of PALF in the mixture made it almost impossible to roll the stabilised soil samples into strips of 3 mm in diameter without breakage. This suggests that an alternative method may need to be developed for clays stabilised with cement-fibres fro a more accurate determination of the plastic limit.
- The liquid limit of the clay has significant influence on the dosage of binder required, where the same amount of binder would have more prominent effect for soils with higher liquid limits.
- The power law relationship between v_s and q_u can be useful for prediction of the strength of cement-PALF stabilised clay soils, as depicted by the high correlation factor (Figure 9). Notwithstanding the irregularities of the pattern in the plastic limit obtained, the consistent trend in strength and stiffness gains (Figures 4 and 5) and minimal scatter of data in Figure 9 do lend confidence to the prediction model.

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