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STRESS-STRAIN-STRENGTH CHARACTERISTICS OF SOFT HONG KONG MARINE DEPOSITS WITHOUT OR WITH CEMENT TREATMENT

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ABSTRACT: This paper presents the results of triaxial tests on soft Hong Kong marine deposits (HKMD) without or with cement treatment. Special attentions are paid to the features of stress-strain relationships and the effective stress paths. Useful correlation (a) between index properties and strength parameters and (b) cement ratio and strength parameters and Young's modulus are presented. The data presented are of practical significance for design and construction of civil works on HKMD in Hong Kong.

INTRODUCTION

A number of large scale reclamation projects have been constructed in Hong Kong, for example, Western Kowloon reclamation and Tseung Kwan O reclamation. More reclamation projects are under construction or to be constructed in the near future. These include the reclamation at the site of Hong Kong Disney in Penny's Bay and at the site of Hong Kong Science Park in Pak Shek Kok in Tolo Harbour, Hong Kong. In all these projects, Hong Kong marine deposits (HKMD) encountered in Hong Kong coastal waters are problematic soils in Hong Kong due to low undrained shear strength and time-dependent high compressibility. Understanding the stress-strain-strength behaviour of HKMD and their improvement have been an urgent issue in Hong Kong. This paper presents main results of triaxial tests on HKMD with or without mixing with cement. The stress-strain-strength characteristics are annualised and discussed. Useful correlation is presented for practical use.

Test Program on HKMD without and with Cement

The marine deposits used in the present test program were taken at depth 1 m to 2 m from seabed in Hong Kong. The marine deposits were of dark grey colour and were a mixture of clay, silt and fine sand with occasional shells and coarse particles. The HMKD was re-consolidated in a stainless steel cylindrical mould of 300 mm in diameter and 450 mm high. Dead weights were placed gradually on the top plate until a maximum pressure of 30 kPa to 40 kPa was reached. The consolidation was checked by monitoring the excess pore water pressure at the bottom of the soil sample using a pressure transducer attached to the bottom of the mould. After consolidation was completed, thin-wall PVC tubes of internal diameter of 75 mm (for oedometer testing) or 50 mm (for triaxial testing) were pushed vertically into the consolidated HKMD sample. Tube samples that were not used immediately were sealed using wax on the top and bottom ends. For oedometer testing, the tube sample was pushed out and trimmed into a specimen of 75 mm in diameter and 19 mm high ready for oedometer testing. A triaxial specimen was prepared using a 50 mm diameter tube sample.

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To get the specimens of HKMD mixed with cement, the pre-consolidated marine deposits at an initial water content of 60%, 80% and 100% were mixed with dry Portland cement powder at four different mass ratios ($A_w = M_{cement}/M_{soil}$), that is, 5%, 10%, 15% and 20%. The mixing process was done using a laboratory size conventional concrete mixer. After thorough mixing, an aluminium cylindrical pipe with an inside diameter of 35 mm and length of 70 mm was pushed into a batch of the cement-mixed marine deposits. The inside surface of the cylindrical pipe was coated with oil to separate the soil from aluminium surface. The cement-mixed M.D. (marine deposits) in the cylindrical pipe was vibrated on a laboratory size vibration table to reduce air voids. If necessary, a palette knife was used to compress and trim the soil and expel trapped air bubbles. All cylindrical pipes with cement mixed M.D. were placed on smooth glass plates. All M.D. specimens in the pipes were covered up by a piece of plastic membrane and cured in air for 1 to 2 days depending on the rate of strength developed in the specimens. After 1 to 2 days of curing in air, specimens were extracted by an extractor and placed in a water tank to be cured for 28 days under a constant temperature of 25°C. After 28 days of curing, the cement mixed M.D. specimens were weighed and the dimensions were measured. Some specimens were used for unconfined compression (UC) testing and some for consolidated undrained (CU) triaxial testing at effective cell pressures of 100 kPa, 200 kPa, and 400 kPa.

Plastic and liquid limit tests, hydrometer tests for size distribution and pH value tests were conducted on the remoulded soil without cement. In UC testing, the speed of vertical compression test was 0.1 mm/min (equivalent to a strain rate of 0.14%/min). A UC test was stopped when the peak strength of the specimen was reached. In CU testing, a back pressure of 200 kPa was applied to ensure that the degree of saturation of the specimen exceeded 95% by checking B-value. Side filter paper strips were placed on the cylindrical surface of the soil specimen to speed up consolidation. The isotropic consolidation conducted in a triaxial cell at a given effective cell pressure lasted from 12 to 24 hours. The speed of vertical compression was 0.2 mm/min (equivalent to a strain rate of 0.28%/min). A CU test normally was stopped after an axial strain larger than 15% was reached. Effective cell pressures used in CU tests were 100, 200, and 400 kPa. After testing, the weight and water content of the specimen were measured. From measured triaxial shear test data, the stress - strain relations of deviator stress ($q=\sigma'_1-\sigma'_3$) and porewater pressure (u) against axial strain (ε) were obtained and plotted. Strength and stiffness parameters were also calculated for analysis.

Composition and Basic Soil Properties

Wet sieving and hydrometer tests were carried out on the HKMD. The particle size distribution curve is shown in Fig. 1. The particle size distribution of the wet-sieved marine deposits was obtained from a hydrometer test. It was found that the marine deposits contained 28% clay (d<0.002 mm), 46% silt (0.002 mm<d<0.06 mm) and 26% fine sand (0.06 mm<d< 0.15 mm). Tests for measuring specific gravity, Atterberg limits, initial water contents (before testing) of HKMD were carried out according to British Standard 1377 (1990). The results for the HKMD are summarised in Table 1.

The point of liquid limit and plasticity index is just above the A-line in plasticity chart. The remoulded marine deposits are classified to be CH, that is, clay of high plasticity. For the controlled initial water contents of w_i=60%, 80% and 100% of the HKMD., the initial void ratios e_i were 1.6, 2.1, and 2.7 respectively. HKMD without cement has a bulk density ρ=1.7 Mg/m^3, dry density ρ_d=1.2 Mg/m^3 and initial water content w_i=42% after re-consolidation.

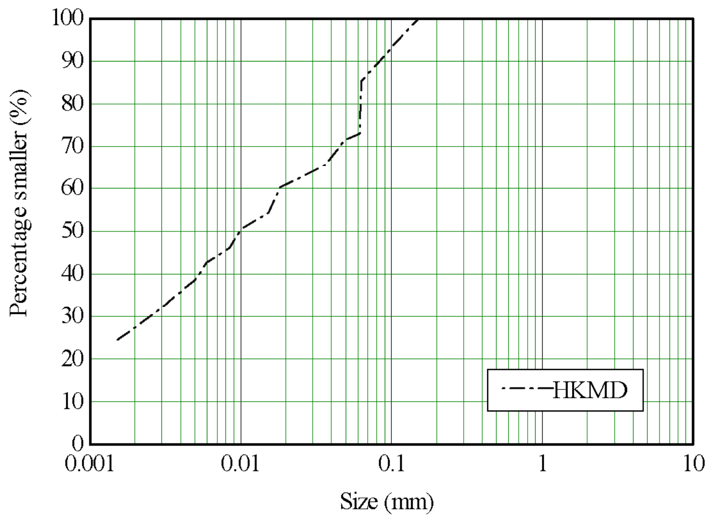

Fig. 1 The particle size distribution of HKMD

Table 1 Specific gravity, Atterberg limits, and water content

	HKMD
Specific gravity, G_s	2.66
Initial water content, w (%)	57
Liquid limit, w_L (%)	60
Plastic limit, w_p (%)	29
Plasticity index, I_p	32

Stress-Strain-Strength Characteristics of HKMD without Mixing with Cement

The main results of three consolidated undrained (CU) triaxial tests on HKMD with cement are shown in Fig. 2. Both the deviator stress and porewater pressure increase with the axial strain as shown in Fig. 2(a) and (b). No peaks are observed. The stress-strain behaviour is typical of normally consolidated clay. The effective cohesion and friction angle are zero and 28^o respectively.

The stress-strain relationship of the HKMD is non-linear. A simple way to describe the stiffness of the soil is to calculate the average Young's modulus E_{50}. E_{50} is defined as the ratio of q_{50}/ε_{50} where q_{50} is a half of the peak deviator stress (q_{peak}) and ε_{50} is the axial strain corresponding to q_{50}, measured from the deviator stress-axial strain curve. The E_{50} is commonly correlated to the maximum (or peak) deviator stress q_{peak}. Figure 3 shows the relationship between E_{50} and q_{peak}. The best straight line fitting to the data points produces

$$E_{50} = 68.3 q_{peak} \tag{1}$$

The Young's modulus basically increases almost linearly with the maximum/peak deviator stress.

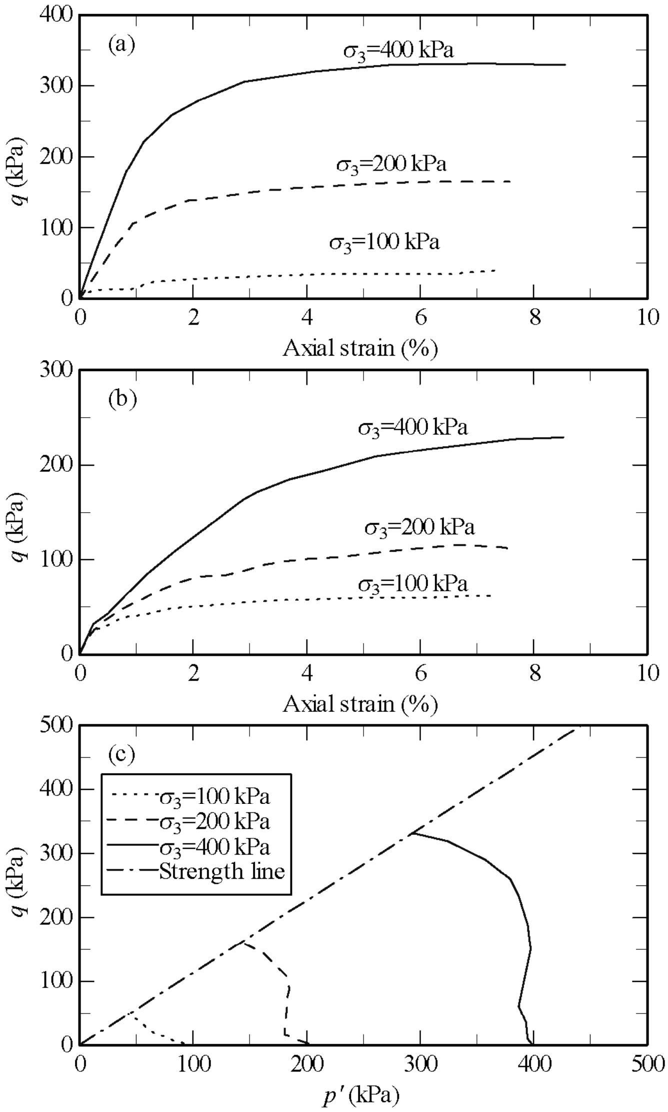

Fig. 2 (a) Deviator stress q *vs.* axial strain, (b) porewater pressure u *vs.* axial strain and (c) effective stress paths for HKMD without cement - σ_3=100, 200, 400 kPa from CU tests

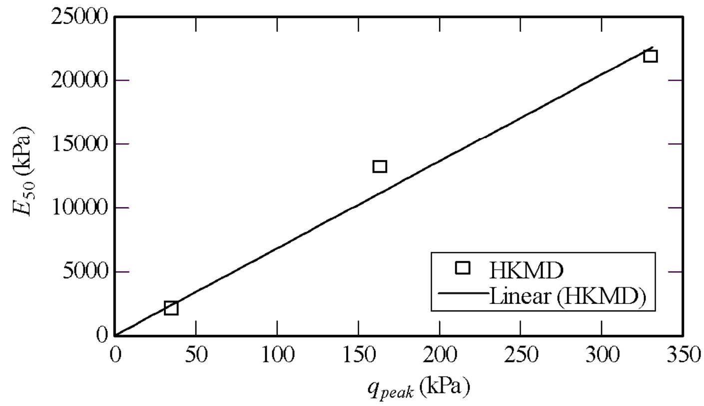

Fig. 3 Correlation of Young's modulus E_{50} with the peak deviator stress q_{peak} for HKMD without cement

Stress-Strain-Strength Characteristics of HKMD Mixed with Cement

Figure 4 shows the curves of axial stress vs. axial strain of cement treated HKMD at A_w=5%, 10%, 15%, and 20% and w_i= 80% (M.C. in the figure) from unconfined compression (UC) tests. It is seen in Fig. 4 that both stiffness and the maximum deviator stress (unconfined shear strength) increase with the ratio A_w. When A_w is 5%, the unconfined shear strength is very small and no significant improvement is observed.

Figure 5 shows (a) deviator stress *vs*. axial strain, (b) porewater pressure vs. axial strain and (c) effective stress paths for A_w=20%, w_i=100% and σ_3=100, 200, 400 kPa from CU tests. The deviator stress increases in general with the confining pressure.

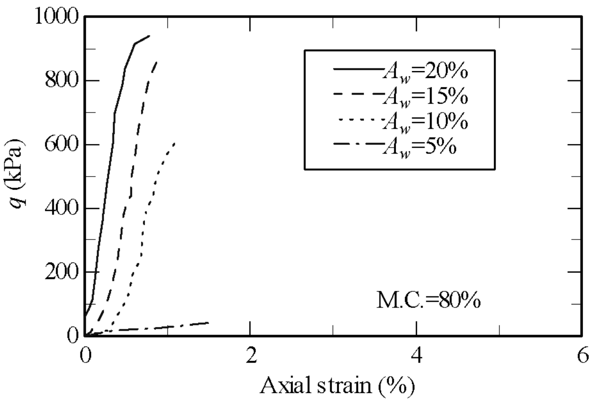

Fig. 4 Curves of axial stress vs. axial stress for A_w=5%, 10%, 15% and 20% with the same w_i.= 80% (M.C.) from UC tests on HKMD mixed with cement

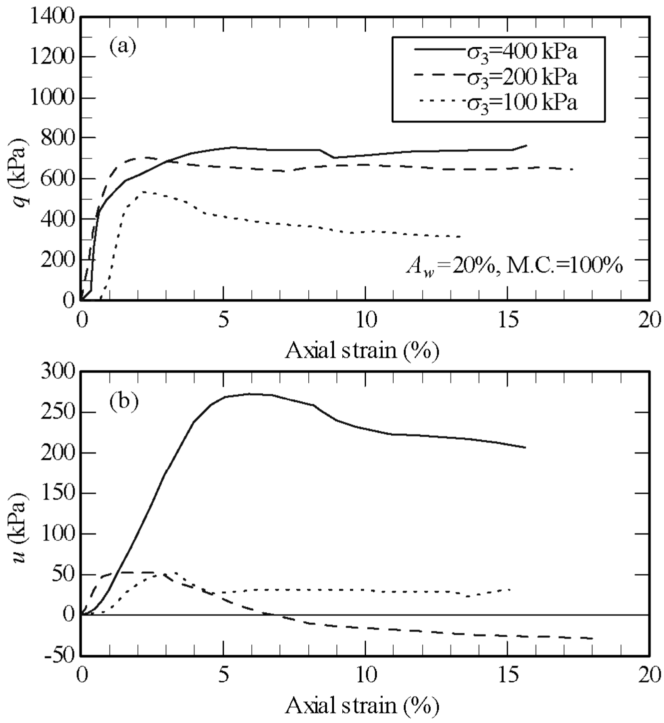

Fig. 5 (a) Deviator stress vs. axial strain, (b) porewater pressure vs. axial strain for A_w=20%, w_i=100% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

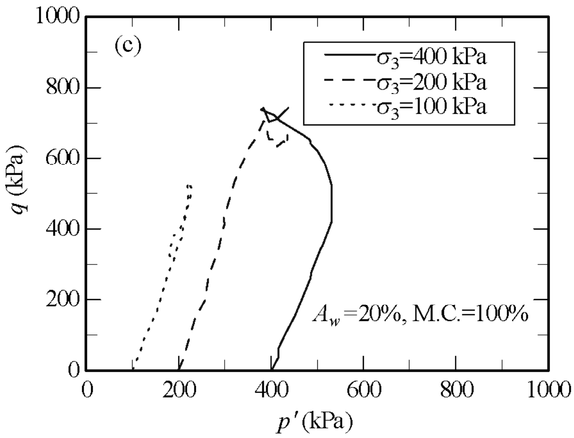

Fig. 5(c) Effective stress paths for A_w=20%, w_i=100% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

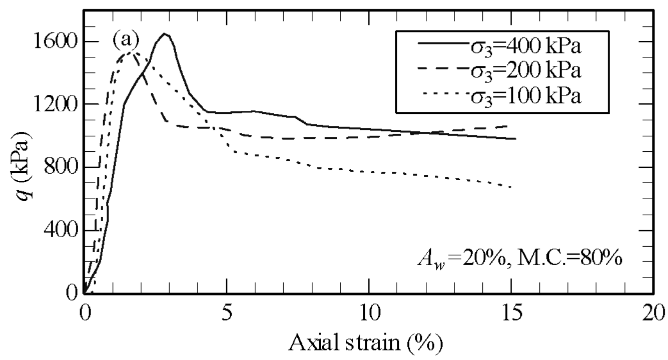

Fig. 6(a) Deviator stress vs. axial strain for A_w=20%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

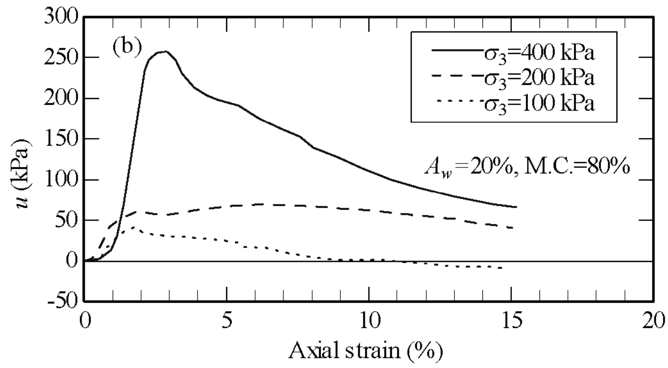

Fig. 6(b) Porewater pressure vs. axial strain for A_w=20%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

Figure 6 shows (a) deviator stress vs. axial strain, (b) porewater pressure vs. axial strain and (c) effective stress paths for A_w=20%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests. The peak of the curves of deviator stress vs. strain is sharper than that in Fig. 5. Figure 7 shows (a) deviator stress vs. axial strain, (b) porewater pressure vs. axial strain and (c) effective stress paths for A_w=20%, w_i=60% and σ_3=100, 200, 400 kPa from CU tests. Comparing to Fig. 5 (w_i=100%), the stiffness and the maximum deviator stresses (peak and residual) in Fig. 8 (w_i=80%) are larger. The HKMD look more over-consolidated. Cementation contributes to the cohesion of the mixed soil. OC (over-consolidation) contributes also to the cohesion, which is not the true cohesion, but apparent cohesion caused by residual suction in the soil. The overall stress-strain and porewater pressures may look similar. Another common feature for Figs. 5, 6, and 7 is that when the confining pressure is large, the soil looks less over-consolidated or closer to the normally consolidated behaviour.

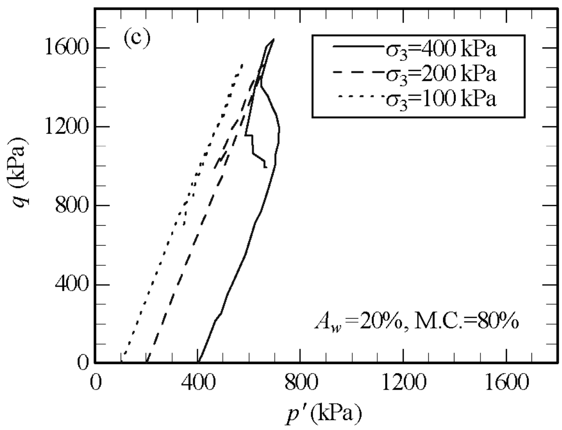

Fig. 6(c) Effective stress paths for A_w=20%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

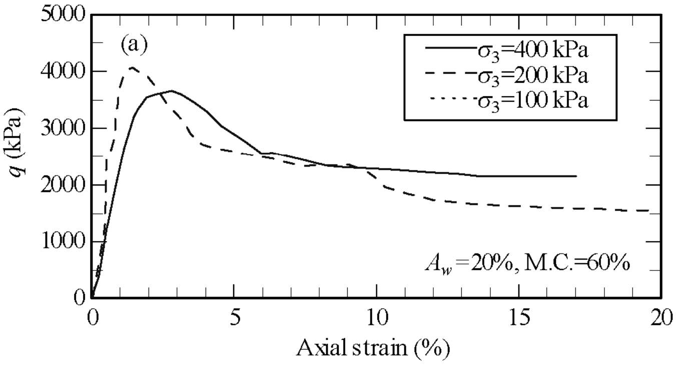

Fig. 7(a) Deviator stress vs. axial strain for A_w=20%, w_i=60% and σ_3=200, 400 kPa from CU tests on HKMD mixed with cement

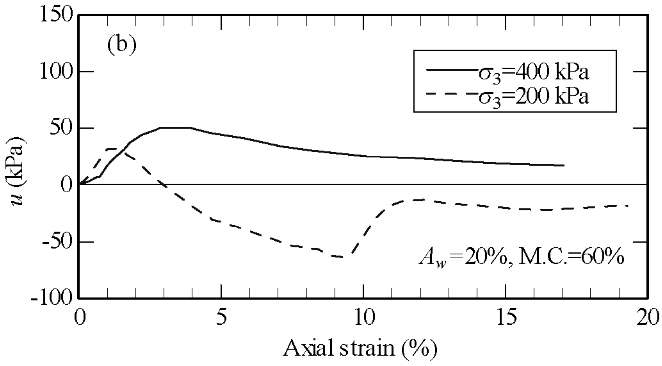

Fig. 7(b) Porewater pressure vs. axial strain for A_w=20%, w_i=60% and σ_3=200, 400 kPa from CU tests on HKMD mixed with cement

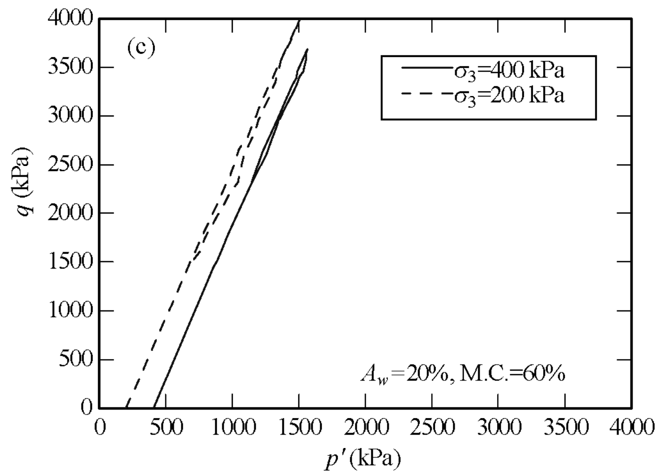

Fig. 7(c) Effective stress paths for A_w=20%, w_i=60% and σ_3=200, 400 kPa from CU tests on HKMD mixed with cement

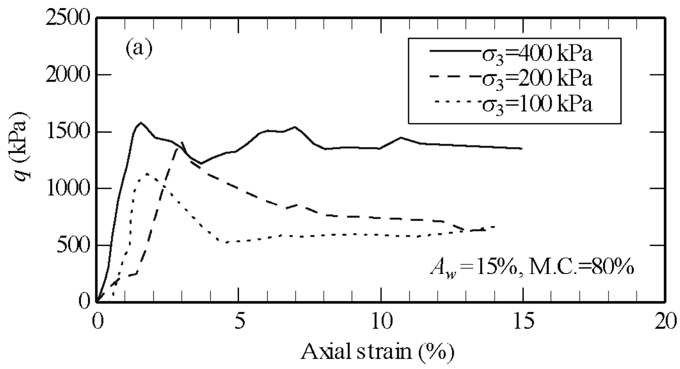

Fig. 8(a) Deviator stress vs. axial strain for A_w=15%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

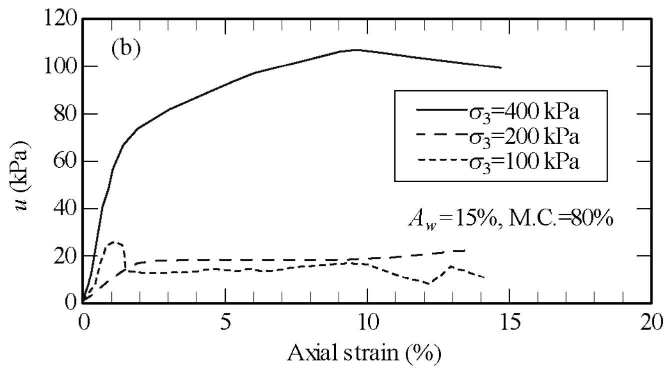

Fig. 8(b) Porewater pressure vs. axial strain for A_w=15%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

For the same initial water content w_i=80%, but different A_w ratios, the deference in the stress-strain behaviour can be found in Figs. 6, 8, 9 and 10. Figure 8 shows (a) deviator stress vs. axial strain, (b) porewater pressure vs. axial strain and (c) effective stress paths for A_w=15%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests. Figure 9 shows (a) deviator stress vs. axial strain, (b) porewater pressure vs. axial strain and (c) effective stress paths for

A_w=10%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests. Figure 10 shows (a) deviator stress vs. axial strain, (b) porewater pressure vs. axial strain and (c) effective stress paths for A_w=5%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests. It is seen that with A_w decreases, the behaviour looks more like a normally consolidated soil.

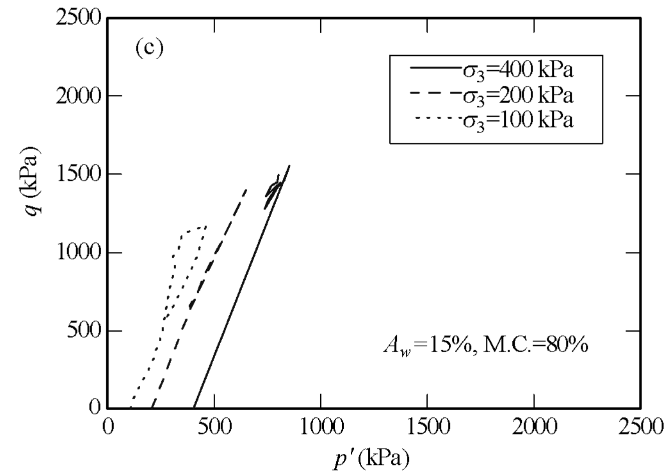

Fig. 8(c) Effective stress paths for A_w=15%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

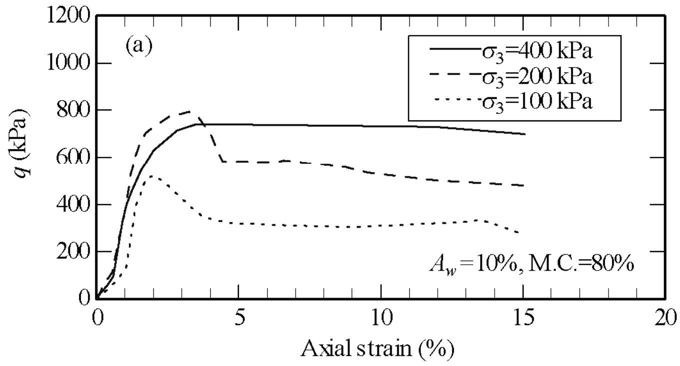

Fig. 9(a) Deviator stress vs. axial strain for A_w=10%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

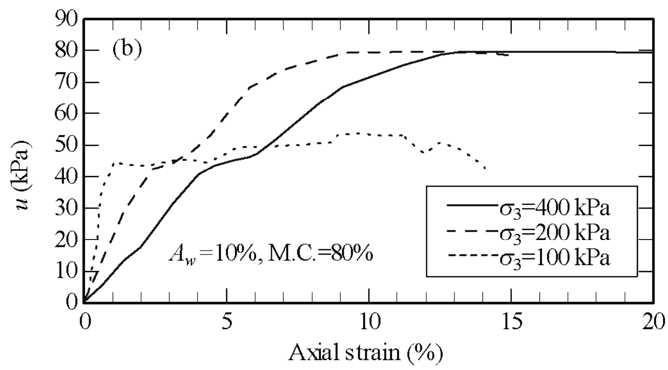

Fig. 9(b) Porewater pressure vs. axial strain for A_w=10%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

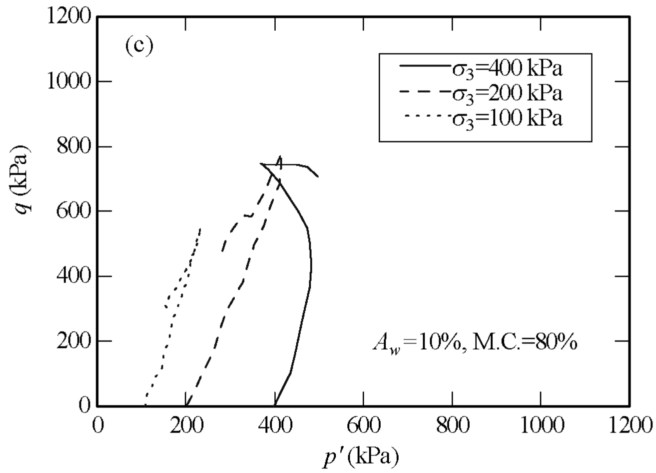

Fig. 9(c) Effective stress paths for A_w=10%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

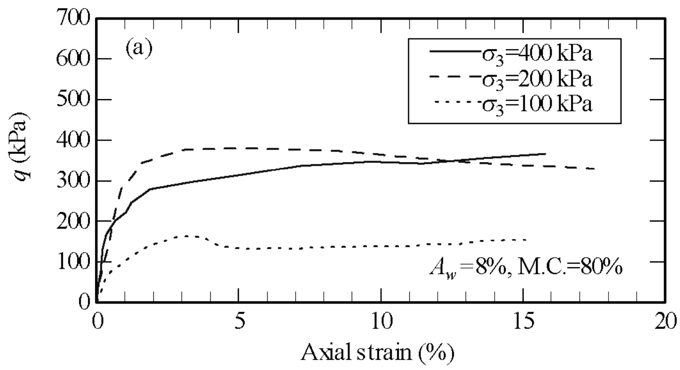

Fig. 10(a) Deviator stress vs. axial strain for A_w=5%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

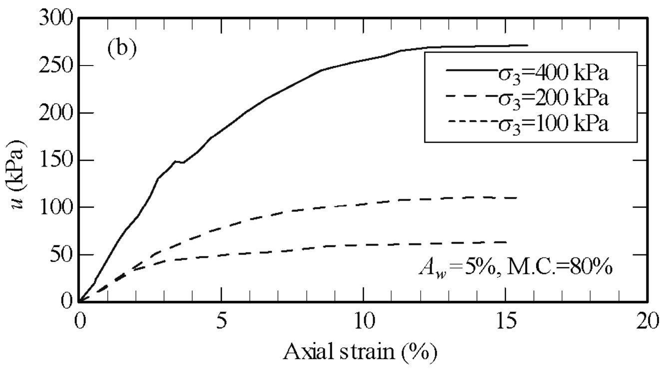

Fig. 10(b) Porewater pressure vs. axial strain for A_w=5%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

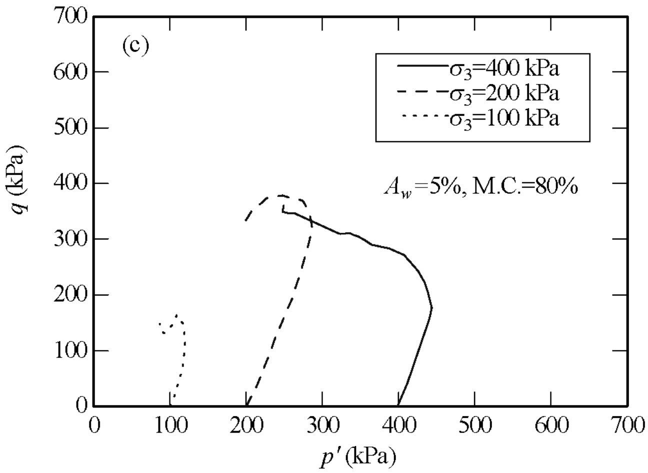

Fig. 10(c) Effective stress paths for A_w=5%, w_i=80% and σ_3=100, 200, 400 kPa from CU tests on HKMD mixed with cement

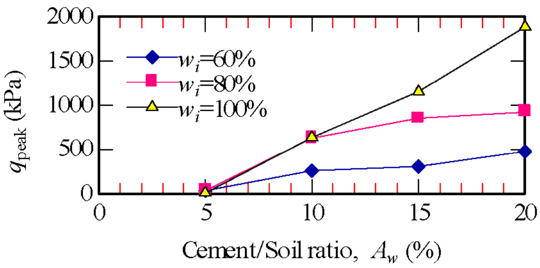

Fig. 11 Peak deviator stress q_{peak} *vs.* A_w and w_i from UC tests on HKMD mixed with cement (after Yin and Lai 1998)

Strength and Stiffness of HKMD with Cement

The initial water content of the marine deposits affects the stress-strain behaviour of cement/soil mixture. The water content in the cement/soil mixture after mixing is normally less than the initial water content and depends on the cement/soil ratio applied. The water reduction in specimens tested varied from 7% to 31%. Higher values of A_w and w_i lead to a relatively greater reduction of water content after cementation. The reduction in water content is due to (a) addition of dry mass of cement and (b) hydration reaction. High initial water contents mean more free water for hydration reaction.

Test data from unconfined compression tests (UC) and consolidated undrained (CU) triaxial tests were used to derive undrained shear strength and Young's modulus as related to cement/soil ratio (A_w) and initial water content (w_i). Figure 11 shows the relationship between peak deviator stress q_{peak} and cement/soil ratio (A_w) and initial water content (w_i). It is found that 5% (A_w=5%) cement does not cause any significant increase of the peak strength of the marine deposits. From this finding, a cement/soil ratio greater than 5%, for example 10% to 20% should be used in order to make significant improvements of the soft Hong Kong marine deposits. It is seen in Fig.11 that the peak deviator stress (q_{peak}) increases with the increase in cement/soil ratio (A_w) and the decrease in initial water content (w_i).

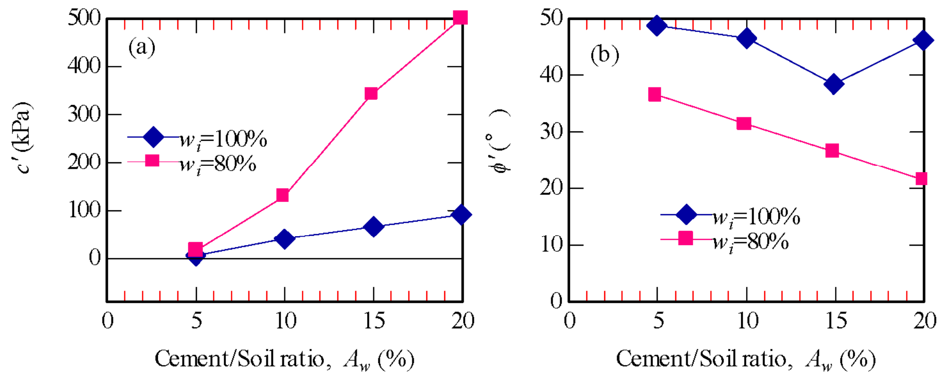

Fig. 12 (a) Cohesion and (b) friction angle ϕ' vs. A_w and w_i from CU tests on HKMD mixed with cement (after Yin and Lai 1998)

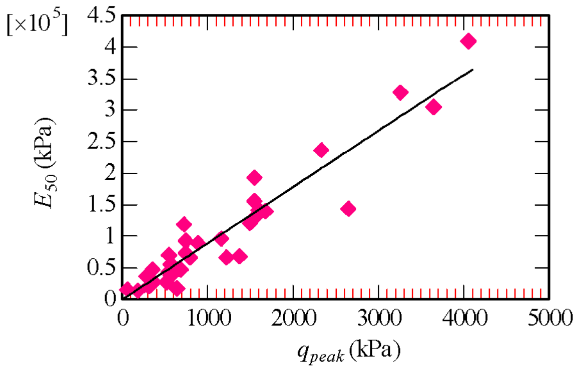

Fig. 13 Correlation between E_{50} and q_{peak} for HKMD mixed with cement (after Yin and Lai 1998)

The relationships of (a) cohesion c$'$ *vs.* A_w and w_i and (b) friction angle ϕ' *vs.* A_w and w_i are shown in Fig. 12(a) and (b). The cohesion c' increases with the increase in A_w and the decrease in w_i. The friction angle ϕ' decreases with the increase in A_w and the decrease in w_i. As cement content (or A_w ratio) increases, the cement treated soil shifts from a Mohr-Coulomb type of frictional material towards a von Mises material with increase in c' and decrease in ϕ'. The calculated E_{50} values with q_{peak} are plotted in Fig. 13. The best fitting line produces

$$E_{50} = 89q_{peak} \tag{2}$$

The correlation coefficient R^2 for the mean value in Fig.13 is 0.91 indicating a good correlation. By comparing Eqn.2 to Eqn.1, the slope value of 89 for HKMD mixed with cement is larger than 68.3 for HKMD without cement.

CONCLUSIONS

This paper has presented (a) typical stress-strain curves and (b) shear strength and Young's modulus for soft Hong Kong marine deposits (HKMD) without or with cement. From the test results, the following conclusions can be drawn on the general characteristics of the stress-strain-strength behaviour of cement-improved soils.

1. Cement hardening/solidification in this soft soil changes the behaviour of the soil from normally consolidated ductile behaviour to over-consolidated brittle behaviour. The strength in terms of peak (q_{peak}) and the stiffness in terms of average Young's modulus (E_{50}) from UC and CU tests increases with (a) the increase in cement/soil ratio (A_w) (b) the decrease in initial water content (w_i) and (c) the increase in confining stress in CU tests. The Young's modulus (E_{50}) increases with the peak deviator stress q_{peak}. For HKMD mixed with cement, the increase of E_{50} with q_{peak} is larger than that for HKMD without cement.

2. No significant improvement of the M.D. was obtained if using a cement/soil ratio of 5% or less. The suggested A_w should be larger than 10%. However, too high a ratio may not be cost-effective.

ACKNOWLEDGEMENT

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