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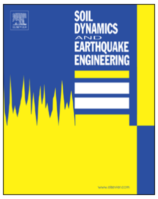

Factors affecting shear modulus degradation of cement treated clay

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Cement stabilization is often used to improve the bearing capacity and compressibility of soft clays. The present paper aims to investigate the shear modulus degradation of cement treated clay during cyclic loading. A series of cyclic triaxial test was conducted on artificially cement treated marine clay to study the factors affecting the shear modulus degradation. The parameters considered for the study are cement content (2.5–7.5%), curing days (7–28), cyclic shear strain amplitude (0.3–1%), number of loading cycles (1–100) and loading frequency (0.1–0.5 Hz). As in the case of natural clays, cement treated clays exhibit stiffness degradation which depends on mix ratio, curing days and loading conditions. The results show that the shear modulus degradation decreases with increase in the shear strain amplitude, cement content and curing days. It is also noted that irrespective of the mix ratio and curing conditions, the degradation decreases with increase in loading frequency. An empirical relationship is proposed to predict the shear modulus degradation based on Idriss's degradation model. The performance of the proposed empirical model is validated with the present experimental results.

1. Introduction

While many studies have been carried out on cement-treated marine clay subjected to static loadings [1–3], the dynamic properties of such treated soils are largely unknown. However in light of rapidly rising demand for cement stabilization in soft soils for urban development in conjunction with the relatively large number of recent earthquakes, a thorough study of the dynamic properties of cement-treated marine clay is of urgent need.

In the past, majority of the studies on dynamic properties of cement treated marine clay was focused to determine the maximum shear modulus at small strains either by the bender element technique [4,5] or using the resonant column apparatus [6–8]. However the cyclic degradation behaviour of cement treated clay subjected to medium to large cyclic strains was not rigorously addressed.

Though there is a lack of understanding on the dynamic properties of cement treated clay, there are a large number of studies reported on nonlinear, hysteretic and stiffness degrading behaviour of natural clay subjected to cyclic loading [9–11]. Idriss et al. [12] introduced the concept of the degradation index to model the reduction in shear modulus with the progression of loading cycles. Vucetic and Dobry [13] proposed the design charts to find degradation as a function of plasticity index, overconsolidation ratio and cyclic shear strain. Zhou and Gong [14] developed the stiffness degradation model of saturated clay considering cyclic shear strain amplitude, cyclic stress ratio, overconsolidation ratio and loading frequency. Li et al. [15] studied the post cyclic strength degradation behaviour of marine clay under long-term cyclic loading. More recently Subramaniam and Banerjee [16] proposed a shear modulus degradation model for cohesive soil considering plasticity index, overconsolidation ratio, loading frequency and cyclic shear strain amplitude.

In summary, preceding discussion shows that whilst the modelling of dynamic behaviour of natural clay is well-established, there are limited numbers of studies conducted on dynamic properties of cement treated clay. Moreover most of those studies concentrated on small strain behaviour of the cement treated clay. Hence there is a need to study the effect of medium to large cyclic shear strains on the behaviour of the cement treated clay. The present paper aims to study the shear modulus degradation behaviour of the cement treated marine clay. Series of undrained cyclic triaxial test (*UCTT*) were performed and effects of various parameters such as, cement content (c), cyclic shear strain amplitude (γ), curing days (d) and loading frequency (f) on the stiffness degradation were studied. Based on the experimental observations, an empirical model was proposed to compute the degradation index of the cement treated marine clay.

2. Experimental programme

Series of strain controlled cyclic triaxial test was conducted on the cement treated marine clay specimens with varying curing

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days, cement content, loading frequencies and cyclic shear strain amplitude. The complete list of different testing conditions is given in Table 1. The low range of cement content was selected to represent the typical stabilized dredged marine clay [17]. Curing days were chosen based on the details available in the literature [5,17]. The cement treated specimens (50 mm in diameter and 100 mm in height) were isotropically consolidated under the confining pressure of 100 kPa. As the effect of the confining pressure on secant shear modulus of cohesive soil is reported to be negligible [18], all the tests are carried out at the same confining pressure. The specimens were subjected to undrained two-way sinusoidal cyclic loading for 100 cycles.

2.1. Specimen preparation

The marine clay samples were collected from Ennore coast of Tamil Nadu, India. The physical and mechanical properties of the clay are shown in Table 2.

Fig. 1a shows the X-ray diffraction pattern of the marine clay used. The plot shows the presence of quartz and feldspar as the silt fraction. It also indicates kaolinite and illite as the clay fraction. Commercially available 53 grade ordinary Portland cement was used for the present study. The X-ray diffraction pattern of the cement (Fig. 1b) shows a clear dominance of calcium silicate.

The cement slurry was gradually added to the remoulded base clay and mixed in a mixer for 10 min at a speed of 61 rpm. The final water content of the clay–cement mix can be obtained from Eq. (1) [19].

$$C_w = w^* + (w/c)A_w \tag{1}$$

where, C_w is the final water content of the clay–cement mix (%), w^* is the water content of the base clay, w/c is the water–cement ratio by weight of the cement slurry and A_w is the cement content as the percentage by weight of the dry base clay. In the present study the water–cement ratio was generally maintained as 0.8. The water content of the base clay was 102%. It should be noted that the effect of water content is significant on the properties of cement treated soil. The cement admixed clay was consolidated in the fabricated sampling tubes with loading frame as shown in Fig. 2. The sampling tubes, made of Fe 316 grade stainless steel, are 50 mm in inner diameter and 200 mm in height. The inner surface of the tubes is polished to minimize the friction between the specimen and the wall of the tube.

Table 1
Different conditions studied in cyclic triaxial tests.

d – Curing (days)	7, 14, 28
f – Loading Frequency (Hz)	0.1, 0.5
c – Cement content (%)	2.5, 5, 7.5
γ – Cyclic shear strain amplitude (%)	0.3, 0.7, 1
N – Number of Cycles	100

Table 2
Physical and mechanical properties of Chennai marine clay used for the study.

Liquid limit, LL (%)	54
Plastic limit, PL (%)	30
Specific gravity, G_s	2.69
Sand (%) (4.75–0.075 mm)	10
Silt size (%) (0.075–0.002 mm)	33
Clay size (%) (< 0.002 mm)	57
pH	7.8
Compression Index, Cc	0.67
Permeability k_v (mm/sec)	5×10^{-7}
Unconfined compressive strength (kPa)	28

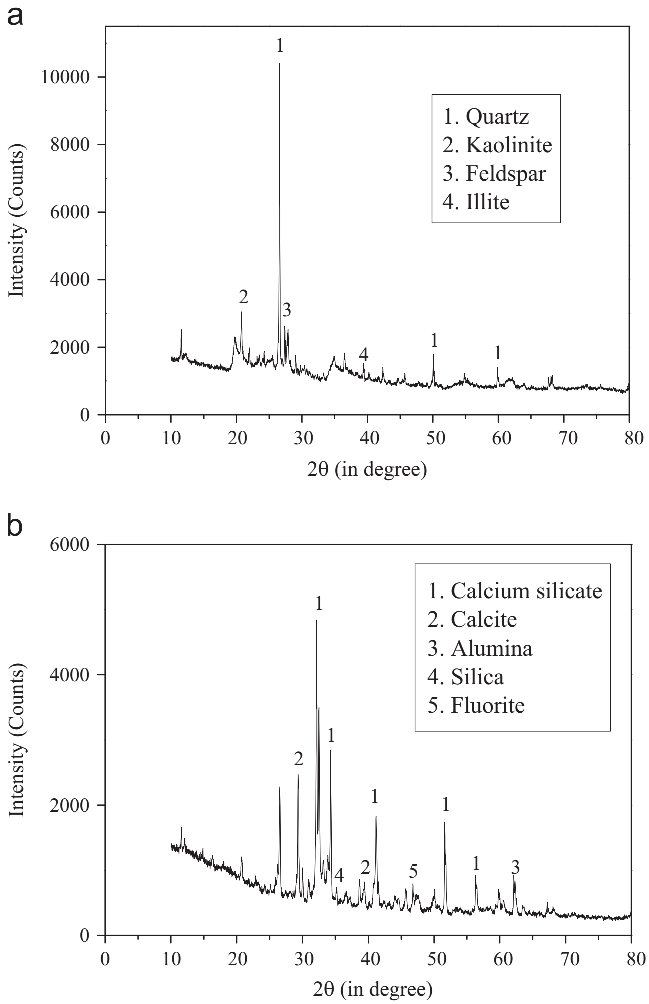

Fig. 1. (a) Powder XRD patterns of the (< 75 μm fraction) marine clay used for the study, (b) Powder XRD patterns of the ordinary Portland cement used for the study.

In order to facilitate the ejection of the specimen, a thin layer of silicone grease was applied in the inner wall of the tube. The cement admixed clay was filled in the sampling tube in 3 stages. After each stage of filling, the cement admixed clay is tamped to remove the entrapped air. In each batch nine specimens were prepared in order to avoid the quick setting. The entire process of filling in the sampling tubes was done in less than 10 min. A detachable porous stone is mounted at the bottom of the sampling tube for bottom drainage. Porous stones are boiled after each and every single use to ensure the free drainage. Filter papers are kept at the top and bottom of the sampling tube to avoid clogging in the drainage path. To allow top drainage, drainage holes are provided in the top cap. Once the top cap is placed, water has been poured at a regular interval (every four days) above the top cap to avoid drying of the specimen. For curing, minimum height of 10 mm water level is maintained above the top cap. To represent the shallow depth, the specimens were loaded for the stress of 30 kPa after 8 h. After the required curing period, the specimen was ejected from the sampling tube. The tube was kept upside down in the sampling extruder in order to maintain a unique loading direction. To ensure the mixing quality and homogeneity of the specimens, three specimens in each batch were tested for unconfined compression test (ASTM D2166) [20] after 7 days of curing period. If the deviation was greater than ±5 kPa from the mean value of the compressive strengths of the specimens, new batch of specimens were prepared. All the specimens were cured in the mist room at the temperature of 27 ± 3 °C and the humidity of