Effect of loading strain-rates on peak strength and drainage behaviour of cement-treated soils

Akanksha Tyagi, Y.-C. Dawn Wong, and F.-H. Lee

Department of Civil and Environmental Engineering, National University of Singapore, 1 Engineering Drive 2, 117576, Singapore

ABSTRACT

This paper examines the effect of loading strain-rates on the unconfined compressive strength and drainage behaviour of the cement-treated soils. Various soil:cement:water mix ratios at curing periods of 7days and 28days were tested at different strain-rates and their peak strength were compared. In addition, drainage behaviour was studied by computing the dimensionless time as well as by visual inspection of excess pore water dissipation from the surface of specimen during different stages of testing. In general, the unconfined compressive strength was found to increase with the increase in strain-rate of testing.

Keywords: cement-treated soil, peak strength, drainage, strain-rate

1 INTRODUCTION

Ground improvement techniques such as cement-treatment are often used to strengthen the soft clayey soils prior to deep excavations and tunnelling. Minimum unconfined compressive strength or peak strength q_u and undrained shear strength c_u are commonly proposed as design requirements for such deep soil mixing or jet grouting projects. Mostly, the unconfined compressive strength tests for cement-treated soils are assumed to take place in undrained situation. However, the consolidation characteristics of cement-treated soils are different from natural soft clays.

Terashi and Tanaka (1983) reported that the rate of consolidation of cement-treated soil columns is significantly faster than that of the surrounding soil. Terashi et al. (1980) observed that the coefficient of consolidation for cement-treated clay soils is about 5 to 50 times that of the untreated clays. Chin (2006) and Xiao (2009) both mentioned about excess pore water pressure dissipation from the sides of unconfined compression test specimens of cement-treated Singapore marine clay during testing. More, recently Tyagi et al. (2017) showed that for cement-treated Singapore marine clays at high cement content of 50%, the unconfined compression test is likely to take place under drained condition, which is attributed to the high stiffness of the improved soil. However, the study was conducted only for few mix ratios at a standard strain-rate of 1mm/min.

The effect of loading-rates or strain-rates are commonly studied for concrete behaviour (Watstein 1953; Fu et al. 1991; Cusatis 2011; Chen et al. 2013). The failure behaviour of concrete is known to be a time-dependent phenomenon and is of significance when dynamic or impact loading is considered. For concrete, in general, the compressive strength increases as the loading-rate increases (Watstein 1953; Fu et al. 1991; Cusatis 2011). While the influence of loading-rates is well-known for concrete, the literature on cement-treated soils is almost nil.

Hence, this paper examines the influence of loading strain-rates on the peak strength q_u and drainage behaviour of cement-treated soils. The effects of loading-rates are studied by conducting unconfined compressive strength tests of cement-treated Singapore marine clay specimens of various soil:cement:water (s:c:w) mix ratios at different strain-rates. Peak strengths of specimens at different strain-rates are compared. The drainage behaviour is studied by quantifying the drainage situation in the form of dimensionless time as well as by visual inspection of excess pore water dissipation from the surface of specimen during different stages of testing.

2 EXPERIMENTAL METHODS

The materials and testing procedure are described in the following subsections.

2.1 Materials

The marine clay used for the preparation of the unconfined compressive strength samples were obtained from the Beach Road, Singapore and had liquid limit and plasticity index of approximately 73% and 41%, respectively. The properties of the Ordinary Portland Cement (OPC) used to treat the marine clay has been reported by Chew et al. (2004) and will not be repeated herein.

2.2 Procedure

The marine clay was first soaked in water and then wet-sieved through 2mm sieve to remove gravels, shells and other coarse impurities. The clay was then stored in the air tight bags at room-temperature to prevent any moisture loss. Ordinary Portland Cement (OPC) and de-ionised water were then mixed into the marine clay to the prescribed mix-ratio. Rheobuild 1000 super-plastizer was also added to increase the workability of the soil-cement mixture. The amount of super-plastizer was kept as approximately 10ml for every 1kg of the dry soil and cement powder. The mixing was done for 10minutes in a Hobart mixer, after which the mixture was transferred to the cylindrical moulds of diameter 50mm and height of 100mm. Five to six specimens were prepared for each case. The samples were then kept for horizontal curing in a tub of water until the day of testing.

2.3 Test Details

Unconfined compressive strength tests were conducted for three soil:cement:water (s:c:w) mix ratios at different strain-rates, as shown in Table 1. For mix ratio of 2:1:3, two curing periods of 7days and 28days were adopted.

Table 1. Details of unconfined compressive strength (UCS) tests

S.No.	Mix ratio s:c:w	Cement content (%)	Water content (%)	Curing Period (days)	Strain-rate (mm/min)
1	5:1:6	20	100	7	0.1,1,10,50
2	10:3:13	30	100	7	0.1,1,10,50
3	2:1:3	50	100	7	0.1,1,10,50
4	2:1:3	50	100	28	0.1,1,10

3 RESULTS

As mentioned in Tyagi et al. (2017), the dimensionless time, T could be used as a measure of drainage situation in an unconfined compressive strength test specimen and is defined as following,

$$T = \frac{c_v t}{r^2} \quad (1)$$

where c_v is the coefficient of consolidation of cement-treated soil, t is the time taken to reach the peak strength in unconfined compressive strength tests and r is the shortest drainage path, which is the radius of the sample, in this case being 25mm. Coefficient of consolidation c_v was calculated as,

$$c_v = \frac{k \times E' \times (1-\nu')}{(1+\nu') \times (1-2\nu') \times \gamma_w} \quad (2)$$

where k is the coefficient of permeability of cement-treated soil adopted as 1×10^{-9}m/s (Kamruzzaman 2003; Chin 2006); E' is the effective Young's modulus and υ' is the Poisson's ratio of the cement-treated soil, kept as 160 times of unconfined compressive strength q_u and 0.2, respectively (Lee et al. 1998; Tan et al. 2002; Kitazume and Terashi 2013; Tyagi et al. 2017); γ_w is the unit weight of water.

The normalised strength ratio q_u/q_{uo} is defined as the ratio of the average strength q_u obtained for any given strain-rate and the average strength q_{uo} which is obtained for the standard strain-rate of 1mm/min. For all the mix ratios (s:c:w), the normalised strength ratios q_u/q_{uo} were plotted against various strain-rates and computed dimensionless times, Figs. 1-2. In general, the mean unconfined compressive strength q_u for standard strain-rate of 1mm/min was higher than for strain-rate of 10mm/min and 50mm/min. In addition, the dimensionless time for strain-rate of 1mm/min was close to 1 or greater than 1 for all the cases, indicating nearly drained situation.

It was found that the weaker specimens (e.g. 5:1:6_7days) show greater variation with strain-rate whereas the stronger specimens (2:1:3_28 days) show less variation. This can be explained by the fact that the coefficient of consolidation increases with the modulus of the soil and therefore increases with stronger specimens. In other words, the stronger specimens consolidate faster than the weaker specimens, which is in agreement with previous literature (Terashi and Tanaka 1983; Terashi et al. 1980). Even at the highest strain-rate, the strongest specimens seem to be behaving in a drained manner. For example, for 2:1:3_28days, the strength ratio q_u/q_{uo} shows less variation for strain-rate of 0.1, 1 and 10mm/min, which corresponds to dimensionless time of 33.4, 4.1 and 0.47, respectively. For such cases, the strain-rate of 1mm/min is more likely to correspond to drained situation.

On the other hand, the 5:1:6_7days specimens show a consistent increase in strength from fast to slow strain-rate, i.e. from undrained to drained. This is also obvious from the stress path, if we consider the undrained stress path to be vertical whereas the drained stress path has a gradient of 3. The drained stress path will intersect the failure envelope or critical state line at a higher q_u value.

From above discussion, it can be said that in general, the unconfined compressive strength, q_u increases as the loading-rate decreases. This is not surprising since a slower loading-rate allows more of the excess pore pressure to dissipate and bring the specimen closer to a drained situation. This is further evident from the close inspection of the specimen during the process of testing. Fig. 3a to 3e shows different stages of testing for a specimen corresponding to the mix ratio of 2:1:3 cured to 7days. The strain-rate was kept as 1mm/min and dimensionless time was computed as ~2. Fig. 3a shows the intact specimen just before the testing. As the loading progresses, the excess pore water starts to appear in the form of tiny water-droplets on the surface of specimen, as shown in Fig. 3b, 3c, 3d. The water-droplets continue to increase up to the stage at which the crack starts to appear. As the cracking continues across the specimen, the water-droplets were sucked inside the specimen and were no longer visible on the sides of the specimen. This phenomenon of appearance of excess pore water or 'sweating' on the sides of specimen just before attainment of the peak strength and re-absorption into the sample afterwards, has also been mentioned by Chin (2006). The re-absorption of excess pore water was attributed to the strain softening and post-peak unloading of the sample (Burland 1990). Thus, the behaviour of cement-treated soils is not same as that of the concrete. This is because the failure behaviour and failure modes of the cement-treated soils depend on their consolidation characteristics and drainage conditions. This was also observed for the improved soil surrounds around tunnels by Tyagi and Lee (2017) in which higher risk of tension failure was observed for smaller dimensionless time.

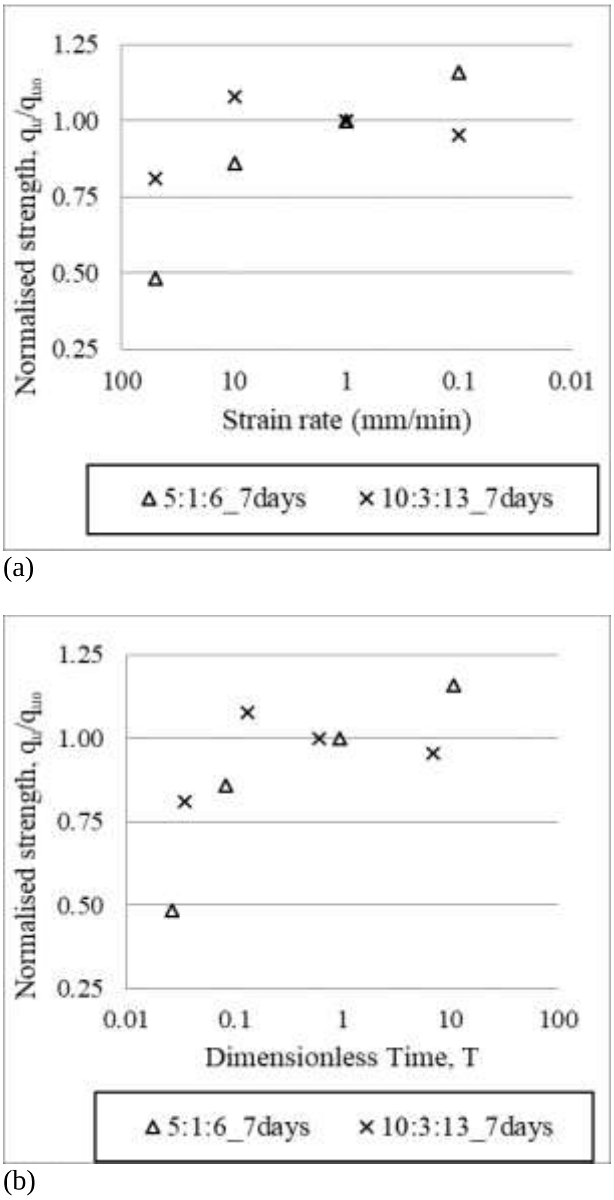

Fig. 1 Normalised strength ratio q_u/q_{uo} plotted against different strain-rates for various mix ratios

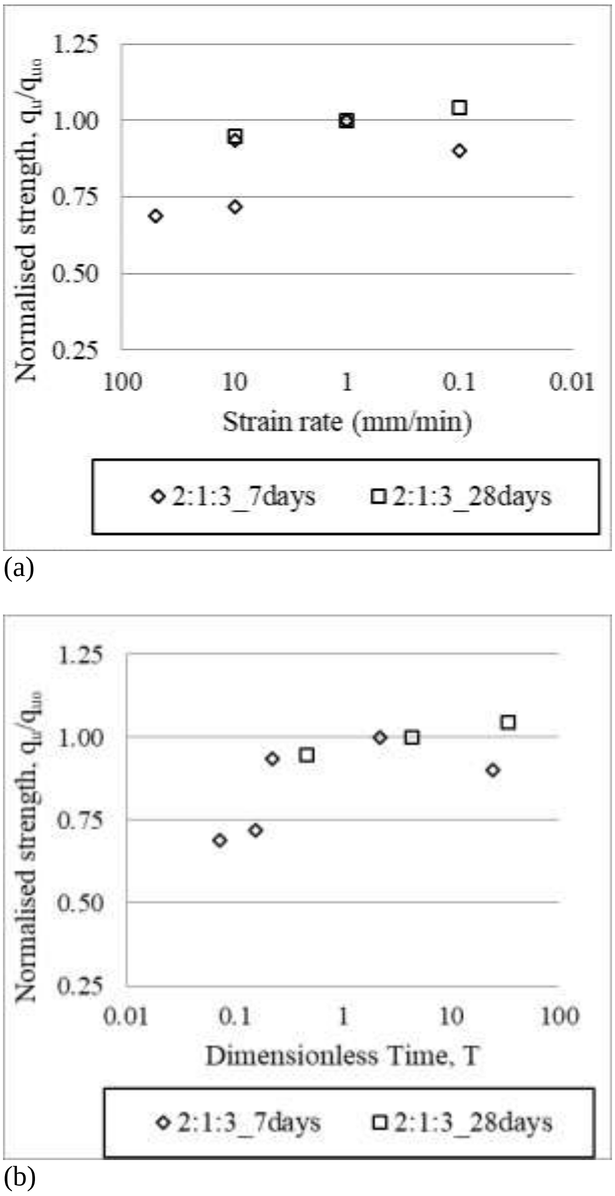

Fig. 2 Normalised strength ratio q_u/q_{uo} plotted against different strain-rates for various mix ratios

3 CONCLUSION

It is found that the unconfined compressive strength for cement-treated soils q_u increases as the loading-rate or strain-rate decreases. This is because a slower loading-rate allows more of the excess pore pressure to dissipate and bring the specimen closer to a drained situation. This behaviour of cement-treated soils is opposite to what has been observed for the concrete. The reason is that the peak strength and failure behaviour of the cement-treated soils depends on their consolidation characteristics and drainage conditions.

This is an important observation and should be taken in consideration while designing geotechnical structures in cement-treated soils in which the loading is time-dependent such as excavation in tunnels, impact or dynamic loading etc.

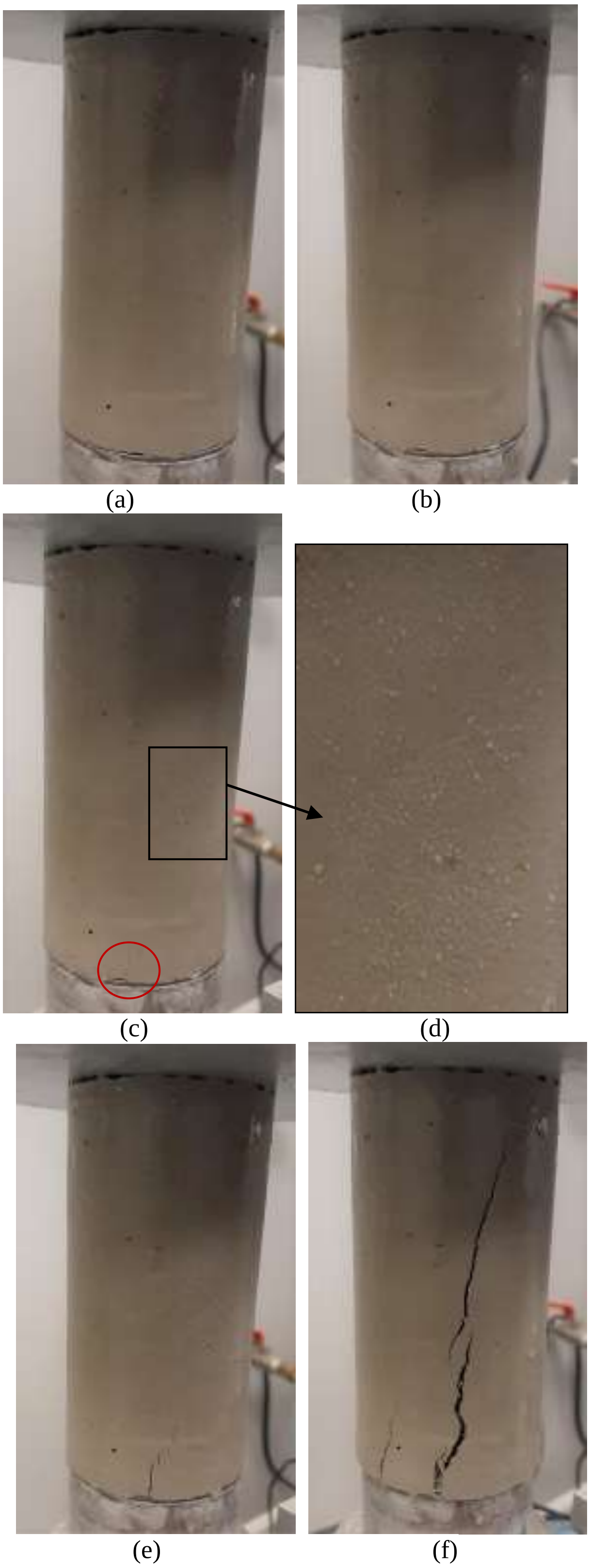

Fig. 3. Specimen 2:1:3_7days, strain-rate 1mm/min (a) Intact specimen just before testing, (b) Water-droplets start to appear on the sides of specimen, (c) Water-droplets increases as crack appears at the bottom of the specimen, (d) Enlarged view of the specimen section showing water-droplets or excess pore water pressure, (e) Water-droplets start to disappear as the crack continues to grow after attaining peak strength, (f) Cracked specimen with almost no water-droplets visible on the surface of the specimen.

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