Shear strength and constant rate of strain consolidation behaviour of cement-treated slurry-consolidated soft soil

Nidal R. Bhuria and Ajanta Sachan*

Department of Civil Engineering, Indian Institute of Technology Gandhinagar 382 424, India

This article focuses on the compressibility and shear strength behaviour of cement-treated soft soil at different cement content and curing time. The soil was found to be too soft (SPT $N = 1$) to collect the undisturbed samples from soil site. Therefore, a pneumatic slurry consolidation set-up has been developed in the laboratory to produce remoulded specimens of soft soil with same *in situ* density and water content. These representative slurry-consolidated remoulded specimens were tested using unconfined compression (UC) and constant rate of strain (CRS) set-up to evaluate the shear strength and compressibility behaviour of soil before and after cement treatment. The conventional 1D consolidation set-up (oedometer) was found to be unsuitable to determine the compressibility behaviour of cement-treated soft soil due to its long testing duration (~10 days), which caused major discrepancy in compressibility results of treated soft soil at the chosen curing time. Thus, the CRS set-up has been developed in the laboratory to accelerate the consolidation process for cement-treated soft soil. A wide range of cement contents (2%, 4%, 6% and 8%) and curing periods (1, 3, 7 and 28 days) were explored to study the compressibility and shear strength parameters of highly compressible soft soil with respect to the cement content and curing time used for its treatment.

Keywords: Cement treatment, constant rate of strain test, soft soil, slurry consolidation.

SOFT soils are known for their high compressibility, low stiffness and low shear strength behaviour. Generally these problems lead to the decision of using deep foundations for soft soil strata even for small structures instead of shallow foundations or they necessitate the need for soil improvement to acquire the desired compressibility, stiffness and shear strength to allow the structures to be placed safely on soft soil strata without undergoing large settlements. Many ground improvement techniques are available such as preloading, vertical drains[1–3], chemical stabilization[4,5], stone columns, jet grouting, lime treatment[6–9], explosive compaction, deep dynamic compaction, compaction grout, vibro replacement[10], electrokinetic injection, geosynthetics[11] and cement stabilization[12–19].

The cement treatment method was chosen over other treatment methods for Kanjur Marg soft soil due to its capability to provide fast increase in strength of soil. Most of the previous studies on soft soil cement treatment[14–16,18–21] were focused on mixing soft soil with different cement content to improve the shear strength properties of soil. However, improvement of compressibility behaviour of cement-treated soft soil was not explored previously using the appropriate consolidation technique which was quick and capable of providing the compressibility parameters of cement-treated soft soil without changing its curing time. The treatment methods used in the previous studies do not replicate field conditions of soft soil cement mixing as the soft soils are generally saturated under *in situ* water content. The slurry consolidation technique was used to incorporate this issue and a pneumatic slurry consolidation set-up was developed in the laboratory to produce the saturated soft soil specimens with the same *in situ* density and water content. These representative slurry consolidated soft soil specimens were used to study the variability effect of cement content (0–8%) and its curing time (0–28 days) on the shear strength and compressibility behaviour of the soil by performing a series of unconfined compression (UC) tests and constant rate of strain (CRS) consolidation tests. Conventional oedometer set-up was found to be inappropriate to evaluate the compressibility characteristics of cement-treated soft soil as the long duration of the test (~10 days) changes the curing time of the cementation process of soft soil during its consolidation, which provides incorrect values of compressibility parameters at the chosen curing time. The CRS consolidometer set-up developed in the laboratory reduced the consolidation time drastically; from 10 days (oedometer) to a few hours (CRS).

Material properties

Soil at Kanjur Marg (Mumbai) site was found to be very soft (SPT $N = 1$) to collect the undisturbed samples; therefore, disturbed representative samples were collected

*For correspondence. (e-mail: ajanta@iitgn.ac.in)

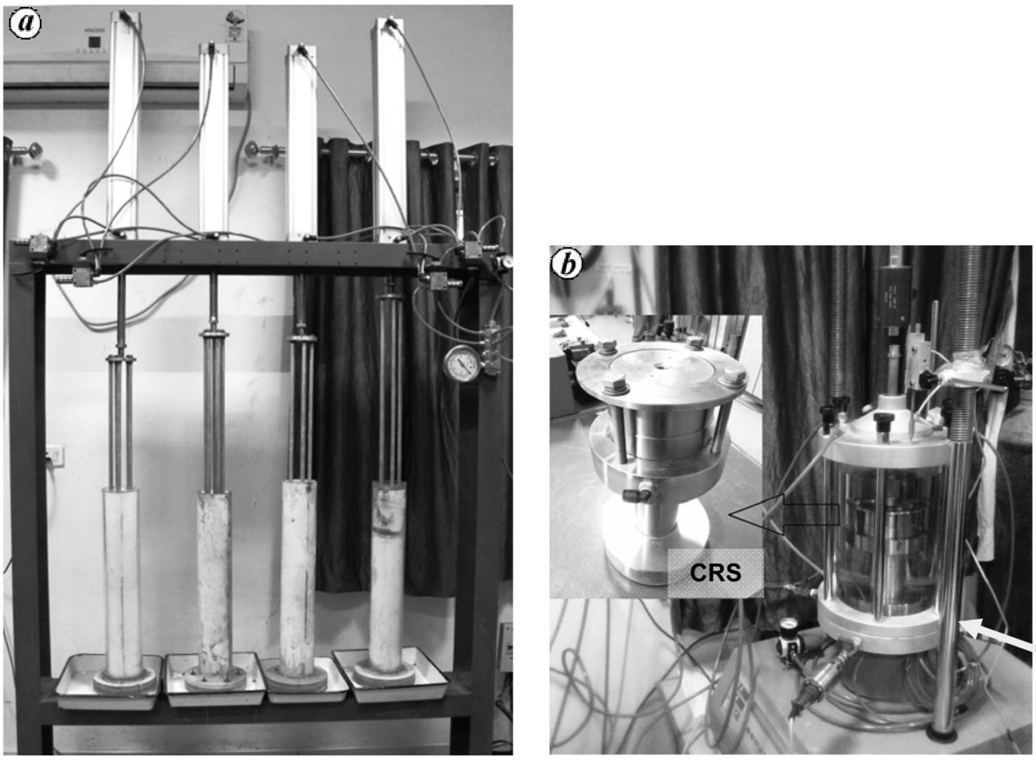

Figure 1. Testing set-up. (***a***) Slurry consolidation set-up (in-house) for preparation of soft soil remoulded specimens. (***b***) CRS consolidation set-up (in-house) for determination of compressibility parameters of cement-treated soft soil.

at 4–5 m depth below the ground surface and brought to the laboratory to prepare the remoulded specimens of soft soil at the same *in situ* density and water content using slurry consolidation technique. The groundwater table was found at 2 m depth below the ground surface. Wet sieve analysis and hydrometer tests were performed on collected soft soil samples with the following soil composition: 47% silt, 50% clay and 3% organic matter (decomposed wood and sea shells, etc). The *in situ* water content and density were observed to be 76% and 1.57 g/cm^3 respectively. The soft soil has liquid limit of 120.7%, plasticity index of 82.6% and specific gravity of 2.77. The Kanjur Marg soil is classified as highly plastic clay, CH, according to IS classification.

Specimen preparation using slurry consolidation technique

Slurry consolidation technique is a method of preparing saturated solid soil samples from soil-water slurry subjected to 1D consolidation under single or double drainage conditions[21]. Consolidation causes the dispersed soil particles in the soil-water slurry to come in contact with each other. The hydraulic conductivity decreases as the slurry gets transformed to solid soil sample; thus, decreased rate of settlement is observed after the soil slurry turns to solid soil state. Slurry is considered to be consolidated when no more settlement is observed over a period of time.

A pneumatic slurry consolidation set-up (Figure 1 *a*) was developed in the laboratory to produce remoulded specimens of soft soil from the soil-water slurry using slurry consolidation technique[22,23]. The prepared soil sample was evaluated for the homogeneity of soil mass by determining the water content and void ratio at various sections of the sample, which indicated that the obtained slurry-consolidated sample was homogenous throughout its volume. Different slurry consolidation pressures (200, 150, 100, 50 KPa) were tried to prepare the remoulded soft soil samples, which could simulate the soil conditions of Kanjur Marg soft soil site and provide the similar geotechnical properties of soil as obtained for undisturbed (UDS) soft soil samples. The samples prepared at 50 kPa of slurry consolidation pressure simulated the *in situ* soil condition 'the best' and showed the similar values of water content, void ratio, density, compression and recompression index as that of UDS soil sample (Table 1).

Soft soil–cement mixture, prepared by mixing varying proportions of ordinary Portland cement (2%, 4%, 6% and 8% of dry weight of soft soil) with representative soil sample (prepared at 50 kPa of slurry consolidation pressure) at water–cement ratio of 0.75, was compacted in a number of layers in a compaction mould and kept in a

Table 1. Engineering properties of slurry-consolidated soft soil specimens prepared at different slurry consolidation pressures. Specimen collected from Kanjur Marg soil site

Consolidation pressure (kPa)	Index properties: Water content (%)	Void ratio	Bulk unit weight γ_t (g/cm^3)	Compressibility parameters (oedometer test): C_c	C_r	Unconfined compressive (UC) strength (q_u, kPa)
200	61.6	1.71	1.63	0.53	0.09	36.6
150	64.4	1.79	1.60	0.59	0.10	25.2
100	68.6	1.90	1.59	0.63	0.11	20.6
50	78.0	2.16	1.56	0.73	0.13	10.9
In situ	76.0	2.21	1.52	0.75	0.12	24.7

C_c, Compression index; C_r, Recompression index.

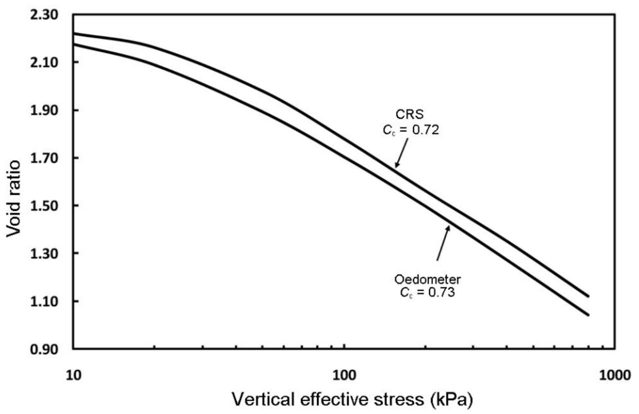

Figure 2. Comparison of stress–void ratio relationship of soft soil specimen prepared at 50 kPa slurry consolidation pressure. Specimens collected from Kanjur Marg soil site.

desiccator for 1, 3, 7 and 28 days curing period. The sample for Atterberg limits of treated soft soil was prepared by gently grinding the lumps of cement-mixed soft soil to a fine powder with a rubber pestle manually and breaking the lumps of clayey soil. This process helps retain the natural individual particle size. Grinding action was preferred over hammering on soil lumps, thus preventing particle crushing.

Experimental programme and CRS set-up

UC and CRS consolidation tests were performed on treated soft soil specimens to evaluate the effect of cement content and curing time on shear strength and compressibility behaviour of cement-treated soft soil. Plasticity index of cement-treated soft soil was also determined to find the effect of cement content and curing time on index properties of treated soil.

The consolidation characteristics of soils are generally determined in the laboratory using conventional 1D consolidation (oedometer) test. In this test, soil stiffness is a function of applied stress and resulting settlement; however, in the case of cement-treated soils, stiffness is a function of applied stress, resulting strain and age (curing time) of the soil. Age or curing time in cement-treated soils plays an important role to control their compressibility properties due to increased curing period of soil while performing the long oedometer tests (testing time = 9–10 days). Long testing duration in the test changes the curing time of the cementation process of soft soil during its consolidation, which provides incorrect values of compressibility parameters of soft soil at chosen curing time. A CRS consolidation set-up (Figure 1 *b*) was developed in the laboratory to accelerate the consolidation process of fine-grained soils with the capability of obtaining the compressibility parameters of such soils before and after their treatment with no change in curing time. CRS test showed a great reduction in consolidation time for treated fine-grained soft soils; from 10 days (oedometer) to a few hours (CRS). The CRS consolidometer applies controlled-strain axial compression to determine the compressibility characteristics of soils with the facility of pore water pressure measurements. Drainage for consolidation was provided from the top and pore pressure was measured at the bottom of the soil specimen.

According to ASTM[24], the strain rate to perform CRS test on cohesive soil needs to be selected based on the pore-water pressure ratio, which is the ratio of base excess pore water pressure to the total axial stress. The strain rate should be chosen in a manner that pore-water pressure ratio during the CRS test is in the range 3–15% for normally consolidated (NC) state. In the present study, 0.005 mm/min strain rate was chosen for loading phase of CRS testing, which exhibited the pore-water pressure ratio to be 14% at the NC state of the soil. Pore-water pressure need not be fully dissipated in the CRS test; this makes it a short-duration test. In the oedometer test, the excess pore-water pressure developed in the specimen under each incremental load is directly related to consolidation as its dissipation is necessary for consolidation to occur. However, in the CRS test, the pore-water pressure is indirectly connected with consolidation by the applied rate of strain. The measured excess pore-water pressure readings supported the applied loading rate of 0.005 mm/min. A strain rate of 0.0025 mm/min was chosen for the unloading phase of CRS testing. Compressibility behaviour of untreated Kanjur Marg soft soil during the CRS test was observed to be similar to that during oedometer test (Figure 2).

Results and discussion

Previous researchers reported that the positive calcium ions from cement get attracted to the negative clay surface replacing other ions and develop a gel-like material on the outer surface of the soil particles due to hydration process[16,20,25]. This results in an increase in the pH value of the pore water, which causes dissolution of the soil silica and alumina from the clay minerals in the presence of calcium ions to form insoluble gel-like compounds. These gel-coated particles of cement are themselves coated all over by the soil particles throughout the mixing process and develop into small crystals following the formation of a huge crystalline network in soil–cement mixture throughout the curing process, resulting in a change in the behaviour of the soil.

Shear strength behaviour

Cementation effect showed a significant improvement in unconfined compressive strength as well as stiffness of treated soft soil (Table 2). Strength gain in cement treatment is entirely dependent on the slower pozzolonic reactions, which are largely completed by the end of 28 days. Curing time has nominal effect on the increase in strength and stiffness of cement-treated soft soil at low cement content (Figure 3 *a* and *b*); however a significant increase in strength and stiffness between 1 and 28 days curing time was observed at high cement contents (Figure 3 *c* and *d*). Moreover, the brittle-type failure at low strain levels was recorded for treated soft soil at 28 days curing period (Figure 3) due to the transformation of pore water to bound water (integral part of hydrated cement-mixed soil particles; double layer) during cementitious reactions, resulting into the formation of hardened crystals of soil–cement within the soil matrix[16,26]. Higher the curing time, higher is the number of hardened crystals of hydrated soil–cement particles formed resulting in the transformation of larger volume of pore water to bound water; thus more pronounced is the brittle behaviour. The increase in unconfined compressive strength at a given curing time was more prominent for soft soil treated with higher cement content than that treated with lower cement content (Figure 4). It can be concluded that unconfined compressive strength of cement-treated soft soil is a function of cement content as well as curing time.

Cement treatment reduced the surface activity of the clay minerals by chemical reactions, which led to significant reduction in liquid limit of soft soil after treatment. As the cement content increased, a significant decrease in liquid limit and small increase in plastic limit was observed resulting into the overall decrease in plasticity index of Kanjur Marg soft soil (Table 2). The variation in curing time also exhibited significant impact in Atterberg limits of soft soil. Similar behaviour was reported for soft soil[20]. Also, the cementation effect and aggregation of soil particles during the treatment of soft soil form the clusters of soil particles. Then the water gets entrapped

Table 2. Shear strength and compressibility (CRS) parameters of soft soil before and after treatment at different cement contents and curing time

Soil	Liquid limit (%)	Plastic limit (%)	UC strength (q_u, kPa)	C_c	C_r	p'_c (kPa)	k (m/s)	m_v (m^2/kN)	c_v (m^2/)
Untreated	120.7	82.6	10.9	0.73	0.13	38	1.6E-10	0.00025	6.5E-08
Cement: 2%; curing: 1 day	120.4	81.6	11.5	0.71	0.12	90	8.6E-11	0.00035	2.4E-08
Cement: 2%; curing: 3 days	113.0	73.5	20.2	0.69	0.07	128	9.9E-11	0.00035	2.8E-08
Cement: 2%; curing: 7 days	108.5	68.9	25.7	0.68	0.05	144	7.2E-11	0.00050	1.4E-08
Cement: 2%; curing: 28 days	105.2	65.1	29.6	0.68	0.05	162	8.8E-11	0.00018	5.0E-08
Cement: 4%; curing: 1 day	107.0	67.8	31.3	0.68	0.05	174	9.9E-11	0.00018	5.6E-08
Cement: 4%; curing: 3 days	100.8	61.7	36.6	0.66	0.05	240	1.4E-10	0.00018	7.7E-08
Cement: 4%; curing: 7 days	94.3	54.8	41.0	0.63	0.05	270	1.5E-10	0.00025	6.0E-08
Cement: 4%; curing: 28 days	90.0	48.7	73.7	0.56	0.04	280	1.4E-10	0.00018	8.1E-08
Cement: 6%; curing: 1 day	97.1	57.1	57.4	0.67	0.04	307	4.5E-10	0.00006	7.6E-07
Cement: 6%; curing: 3 days	94.0	51.2	67.7	0.63	0.04	329	1.2E-10	0.00018	6.9E-08
Cement: 6%; curing: 7 days	87.7	44.3	81.5	0.60	0.03	350	1.8E-10	0.00018	1.0E-07
Cement: 6%; curing: 28 days	81.0	36.9	172.8	0.50	0.03	400	3.3E-10	0.00043	7.8E-08
Cement: 8%; curing: 1 day	95.2	51.2	69.6	0.60	0.03	364	4.4E-10	0.00018	2.5E-07
Cement: 8%; curing: 3 days	88.3	43.8	83.4	0.47	0.03	386	2.7E-10	0.00035	7.7E-08
Cement: 8%; curing: 7 days	83.1	37.7	115.0	0.40	0.03	427	3.3E-10	0.00009	3.7E-07
Cement: 8%; curing: 28 days	74.2	25.5	278.4	0.28	0.02	487	9.1E-10	0.00035	2.6E-07

C_c, Compression index; C_r, Recompression index; p'_c, Preconsolidation pressure; k, Permeability; m_v, Coefficient of volume compressibility; C_v, Coefficient of consolidation.

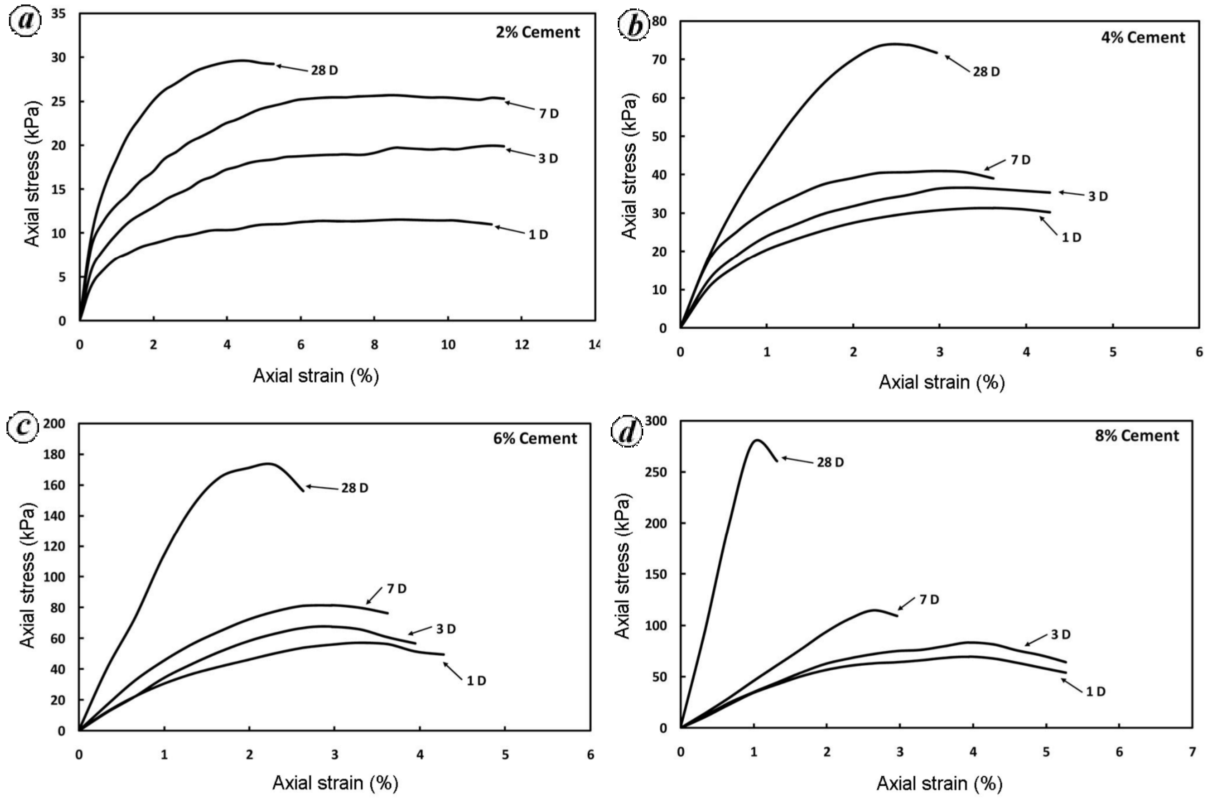

Figure 3. Effect of curing time on unconfined compressive strength of soft soil treated at different cement contents: (***a***) 2%, (***b***) 4%, (***c***) 6% and (***d***) 8%.

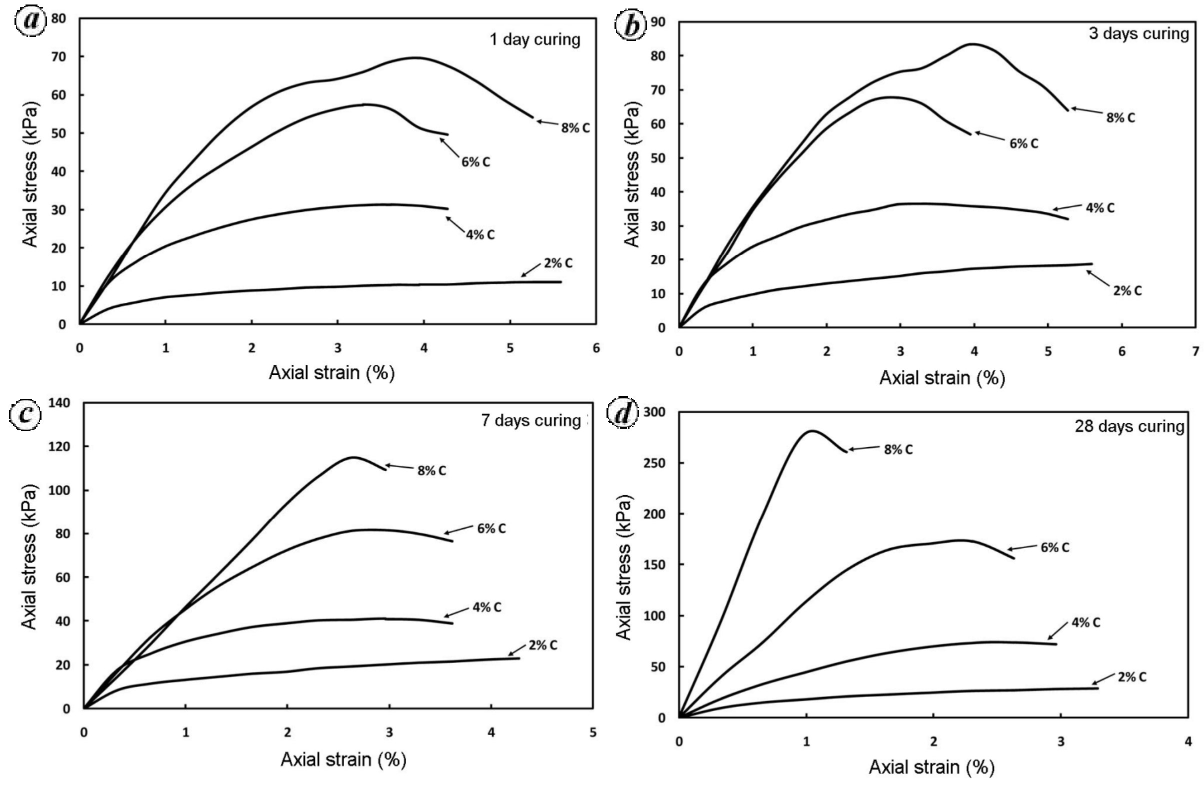

Figure 4. Effect of cement content on unconfined compressive strength of soft soil at different curing periods: (***a***) 1 day, (***b***) 3 days, (***c***) 7 days and (***d***) 28 days.

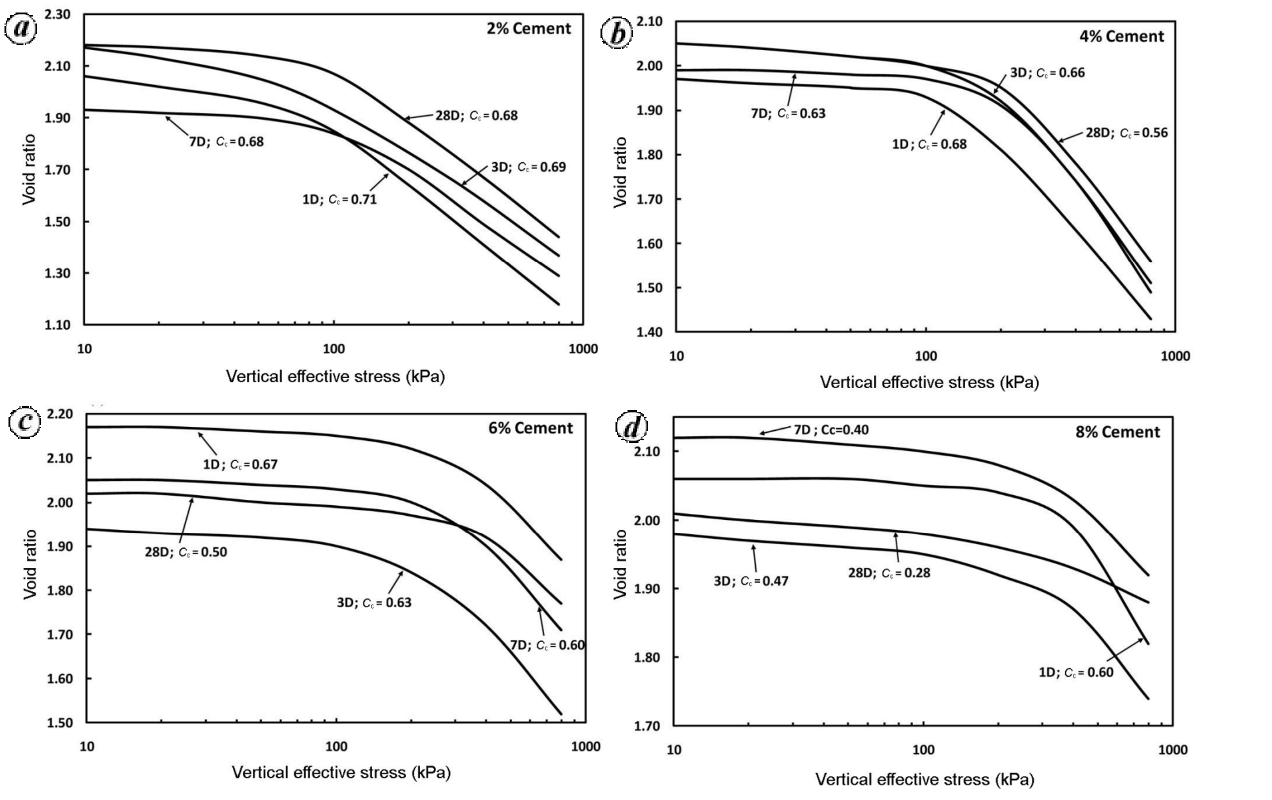

Figure 5. Relationship between curing time and compression index of soft soil for different cement contents: (***a***) 2%, (***b***) 4%, (***c***) 6% and (***d***) 8%.

within intra-particle pores of the clusters of soil particles without affecting the interaction between the particles, thus causing an increase in plastic limit of the cement-treated soft soil. The encapsulation of the clay particles by deposited cementitious products decreases the specific surface area of the cemented soil clusters, causing a decrease in the liquid limit throughout the curing process.

The effect of inclusion of cement changed the behaviour of soft soil causing an increase in unconfined compressive strength from 10.9 (untreated soil) to 278.4 kPa and a decrease in plasticity index from 82.6% (untreated) to 25.5% for soil samples treated with 8% cement content up to 28 days curing time.

Compressibility behaviour

The coefficient of volume compressibility (m_v), permeability (k), compression index (C_c), recompression index (C_r), preconsolidation pressure (p'_c) and coefficient of consolidation (c_v) of treated soft soil have been obtained, as listed in Table 2. A significant improvement in permeability was observed; however, compression index showed significant decrease as the cement content increased in soft soil. Cement affected the geometric arrangement and bonding between the soil particles, which strengthened the soft soil matrix causing a significant decrease in compression and recompression indices and increase in preconsolidation pressure for cement-treated Kanjur Marg soft soil (Table 2). The strength and number of induced cementation bonds increased with curing time; thus settlement reduced with curing time. Curing time effect on consolidation properties of cement-treated soft soil was suppressed at low cement content (2%); however more than 60% decrease in C_c and 85% decrease in C_r values were observed at higher cement contents (6% and 8%) with 28 days of curing. The soil skeleton was observed to be more strengthened when larger amount of cement was used for treatment resulting in small settlement. Preconsolidation pressure was determined analysing the stress–void ratio curves using Casagrande graphical method. The preconsolidation pressure of soft soil was observed to increase with the increase in cement content and curing time. p'_c was found to be 38 kPa for untreated soft soil; which showed great improvement after treatment of soil with different cement contents, 2%, 4%, 6% and 8% and exhibited much higher values of p'_c, i.e. 162, 280, 400 and 487 kPa at 28 days of curing. Major microstructural changes, including the breakdown of inter-particle cementitious bonds and corresponding displacements might have begun to occur when the pressure applied on the soil exceeded the preconsolidation pressure; which defined the range between stiff and soft deformation response of cement-treated soft soil in recompression and virgin compression stage of

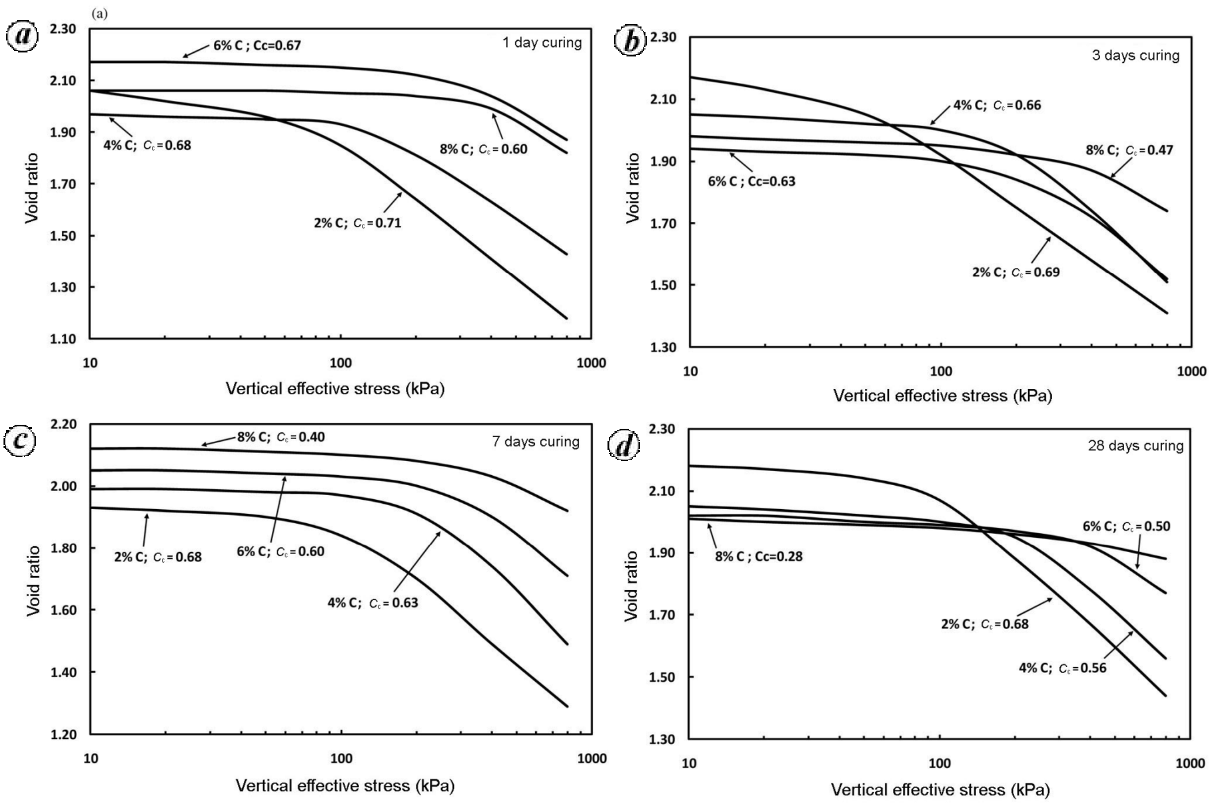

Figure 6. Relationship between cement content and compression index of soft soil at different curing periods: (***a***) 1 day, (***b***) 3 days, (***c***) 7 days and (***d***) 28 days.

CRS consolidation testing. The behaviour of cement-treated Kanjur Marg soft soil was observed to change from normally consolidated to overconsolidated state, which indicated that the void ratio remained practically unchanged when the cement-treated soft soil specimen experienced recompression stage of loading during CRS testing. Parallel virgin consolidation curves were observed for all soft soil samples treated with different cement contents and curing time (Figures 5 and 6), indicating the cementitious effect to be more significant in recompression phase, than in the phase after the preconsolidation pressure.

Conclusion

A series of slurry consolidation tests at different anisotropic consolidation pressures were performed on Kanjur Marg soft soil to acquire the remoulded specimens simulating the *in situ* soil conditions. These slurry-consolidated specimens were used to perform the CRS consolidation and UC tests to evaluate the compressibility and shear strength behaviour of soft soil before and after cement treatment. The widely used and easily available ordinary Portland cement was chosen for the treatment of soft soil for different cement contents varying from 0% to 8% of dry mass of soil for curing time from 1 to 28 days to evaluate the engineering behaviour of treated soft soil. Key observations from this study are summarized as follows:

- Cementation effect improved the shear strength and stiffness of treated soft soil due to the formation of crystalline network of hydrated cement particles throughout the soft soil matrix. Hydration of cement transformed the pore water to bound water resulting into the formation of hardened crystals of soil–cement mixture, resulting into the brittle failure of soil at low strain levels. A significant decrease in plasticity index (82.6–25.5%) was observed after cement treatment of the Kanjur Marg soft soil.
- Compressibility of treated soft soil was observed to be a function of cement content and curing time. Cement treatment strengthened the soft soil matrix by bonding the soil particles, leading to a decrease in compressibility parameters of treated soft soil. Also, 60% decrease in C_c and 85% decrease in C_r values were observed when the soil was treated with 8% cement at 28 days of curing time.
- Cement treatment showed the significant increase in preconsolidation pressure of soft soil. When the

pressure applied on soil during CRS testing exceeded the preconsolidation pressure, stiff and soft deformation response of the cement-treated soil was observed in recompression and virgin compression stages respectively.

1. Broms, B. B., Stabilization of very soft clay using geofabric. *Geotext. Geomembr.*, 1987, **5**, 17–28.
2. Ali, F. H. and Huat, B. K., Performance of prefabricated vertical drains in improvement of Malaysian soft marine clay. In Third International Conference on Case Histories in Geotechnical Engineering, Missouri, 1993, vol. 7.13, pp. 989–994.
3. Attya, A., Indraratna, B. and Rujikiatkamjorn, C., Effectiveness of vertical drains in dissipating excess pore pressures induced by cyclic loads in clays. In Proceedings of the 16th Southeast Asian Geotechnical Conference, Selangor, Malaysia, 2007, pp. 447–451.
4. Kazemian, S. and Huat, B. K., Assessment of stabilization methods for soft soils by admixtures. In International Conference on Science and Social Research, Kuala Lumpur, Malaysia, 2010, pp. 118–121.
5. Kazemain, S. and Barghchi, M., Review of soft soils stabilization by grouting and injection methods with different chemical binders. *Sci. Res. Essays*, 2012, **7**(24), 2104–2111.
6. Cai, Y., Shi, B., Tang, C. and Wang, B., Pilot study on the mechanical behaviour of soil with inclusion of polypropylene fibre and lime. *Int. Assoc. Eng. Geol. Environ.*, 2006, **637**, 1–6.
7. Uddin, M. K. and Buensuceso, B. R., Engineering properties of and a conceptual model for lime treated clay. *J. Civ. Eng. Inst. Eng., Bangladesh*, 2000, **28**(2), 169–187.
8. Rajasekaran, G. and Rao, S. N., Compressibility behaviour of lime treated marine clay. *Ocean Eng.*, 2002, **29**, 545–559.
9. Liu, M. D., Pemberton, S. and Indraratna, B., A study of the strength of lime treated soft clays. In International Symposium and Exhibition on Geotechnical and Geosynthetics Engineering: Challenges and Opportunities in Climate Change, Bangkok, Thailand, 2010, pp. 245–251.
10. Raju, V. R., The behaviour of very soft soils improved by vibro replacement. In Ground Improvement Conference, London, 1997, vol. 12–64E.
11. Loke, K. H., Toh, C. T. and Chee, S. K., Geotextile-bamboo composite construction – Malaysian experience and economic method for stabilization and reclamation of soft soils. LARREN'97, 1997, pp. 212–218.
12. Ho, M. H. and Chan, C. M., Some mechanical properties of cement stabilized Malaysian soft clay. *World Acad. Sci. Eng. Technol.*, 2011, **74**, 24–31.
13. Saadeldin, R., Salem, M. A. and Lofti, H. A., Performance of road embankment on cement stabilized soft clay. In 2011 Pan-Am CGS Geotechnical Conference, Toronto, Canada, 2011.
14. Ghosh, A., Samanta, M., Sharma, S., Jain, S. K. and Kumar, D., Estimation of unconfined compressive strength of cement treated soft Indian coastal clay. In Proceedings of Indian Geotechnical Conference, Kochi, 2011, vol. 323, pp. 1109–1112.
15. Bushra, I. and Robinson, R. G., Strength behaviour of cement stabilized marine clay cured under stress. In Indian Geotechnical Conference 2010, GEOtrendz, IGS Mumbai Chapter and IIT Bombay, 2010, pp. 601–604.
16. Xiao, H. W. and Lee, F. H., Curing time effect on behaviour of cement treated marine clay. *Int. J. Eng. Appl. Res.*, 2009, **5**(7), 427–434.
17. Chan, C. M. and Abdullah, S. H., Settlement behaviour of a cement stabilized Malaysian clay. In 6th International Conference on Case Histories in Geotechnnical Engineering, Arlington, VA, USA, 2008, vol. 7.41a, pp. 1–6.
18. Kamruzzaman, A. H. M., Chew, S. H. and Lee, F. H., Engineering behaviour of cement treated Singapore marine clay. In GeoEng2000 – An International Conference on Geotechnical and Geological Engineering, Melbourne, Australia, 2002, No. 1190, pp. 1–7.
19. Tan, T. S., Goh, T. L. and Yong, K. Y., Properties of Singapore marine clays improved by cement mixing. *Geotech. Testing J.*, 2002, **25**(4), 1–12.
20. Chew, S. H., Kamruzzaman, A. H. M. and Lee, F. H., Physicochemical and engineering behaviour of cement treated clays. *J. Geotech. Geoenviron. Eng.*, 2004, **130**(7), 696–706.
21. Bo, M. W., *Compressibility of Ultra Soft Soil*, World Scientific Printers, Singapore, 2008.
22. McConnachie, I., Fabric changes in consolidated kaolin. *Geotechnique*, 1974, **24**(2), 207–222.
23. Penumadu, D., Skandarajah, A. and Chameau, J. L., Strain-rate effects in pressuremeter testing using a cuboidal shear device: experiments and modelling. *Can. Geotech. J.*, 1998, **35**(1), 27–42.
24. ASTM, Standard test method for one-dimensional consolidation properties of saturated cohesive soils using controlled-strain loading, American Society for Testing and Materials, Pennsylvania, USA, 2006.
25. Rahman, M. M., Siddique, A. and Uddin, M. K., Microstructure and chemical properties of cement treated soft Bangladesh clays. *Soils Found., Jpn. Geotech. Soc.*, 2010, **50**(1), 1–7.
26. Zhu, W., Zhang, C. L. and Chiu, A. C., Soil-water transfer mechanism for solidified dredged materials. *J. Geotech. Geoenviron. Eng.*, 2007, **133**(5), 588–598.

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