KSCE Journal of Civil Engineering (0000) 00(0):1-12

DOI 10.1007/s12205-017-1686-3

Geotechnical Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Strength and Dynamic Properties of Cement-Mixed Korean Marine Clays

Ah-Ram Kim*, Ilhan Chang, Gye-Chun Cho***, and Seong-Hyeon Shim******

Received October 10, 2016/Revised March 7, 2017/Accepted April 13, 2017/Published Online July 14, 2017

Abstract

Deep Cement Mixing (DCM) is the most commonly employed ground improvement method for offshore construction purposes worldwide. Nevertheless, the dynamic behavior of cement-mixed and stabilized clays is almost unknown due to the lack of experimental studies, while seismic concerns regarding offshore structures related to typhoons, tsunamis, or earthquakes are becoming more important. Moreover, very few geotechnical evaluations have been performed to characterize cement-mixed Korean marine clays, while DCM is the most commonly used practical implementation method for soft soil improvement in Korea. In this study, a series of laboratory experimental studies were conducted to obtain the static strengthening and dynamic behaviors and geotechnical engineering design parameters of cement-treated Korean marine clays. The unconfined compressive strength and shear stiffness (G) of cement-mixed Korean marine clay increase with curing time, while different trends were observed for strain-dependent behaviors (i.e. normalized shear modulus and damping ratio) depending on curing time and binder contents. The static and dynamic geotechnical properties and relationships of DCM treated soft clays obtained in this study are expected to be accepted for seismic considerations and designs of DCM-treated soft clays.

Keywords: *Deep Cement Mixing (DCM), Marine clay, Unconfined strength, Resonant Column (RC), Shear modulus, G/G_{max} curve, Seismic stability, Shear wave*

1. Introduction

Geological formation and geotechnical engineering behaviors of soft soil depend on soil type and composition, mineral constitution, sedimentation process, particle alignment, and so on (Maher and Ho, 1994; Quigley, 1980). In cases where soft soil has to be used as a foundation geometry for offshore or marine structures (*e.g.*, for a harbor or breakwater), soft marine deposits can induce critical geotechnical problems due to insufficient bearing capacity or consolidation related issues (*e.g.*, large or differential settlement). Therefore, numerous soft ground improvement technologies such as hydraulic modification, soil densification, physical and chemical modification, and modification with inclusions and confinement have been investigated to improve the strength and stability of soft soils in the field (Nicholson, 2014).

Deep Cement Mixing (DCM) is one of the most commonly used implementation methods for soft soil improvement in many countries to provide reinforced *in situ* soil foundations for offshore harbor and port structures such as quay walls and seawalls. The DCM method was suggested in the 1960s by the Japanese Port and Airport Research Institute (formerly the Port and Harbor Research Institute) and the Swedish Geotechnical Institute (SGI). Initially lime was used and then cement-based binders were deployed in practical applications. Recently, gypsum, fly ash, cement, and slag-based binders have been widely used for particular purposes (Holm). The main principle of cement mixing is to create chemical bonds (C-S-H crystals) between soil particles due to the hydration reaction of cement binders. When a cement-water slurry is injected into the ground, cement hydration and pozzolanic reactions occur simultaneously; this induces cementitious matrices in soil pores, providing permanent stabilization (Cokca, 2001; Kezdi, 1979; Schaefer *et al*., 1997). Moreover, the increase in strength accompanies an increase in stiffness, and cement-treated soils show lower compressibility and permeability compared to untreated soils (Asano *et a*l., 1996; Consoli *et al*., 2015; Futaki *et al*., 1996). The DCM method offers economical and technical advantages including high strength, a shorter construction period, versatile applicability to most soil types, low material (*i.e.*, cement) costs, and relatively

*Research Specialist, Future Strategy & Convergence Research Institute, Korea Institute of Civil Engineering and Building Technology (KICT), Goyang 10223, Korea (E-mail: kimahram@kict.re.kr)
**Member, Lecturer, School of Engineering and Information Technology, University of New South Wales, Campbell, ACT 2600, Australia (E-mail: Ilhan.chang@adfa.edu.au)
***Member, Professor, Dept. of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, Korea (Corresponding Author, E-mail: gyechun@kaist.edu)
****General Manager, Engineering & Construction Group, Samsung C&T Corporation 13530, Korea (E-mail: symmoon@samsung.com)

lower noise and vibration than other field construction methods (Lin and Wong, 1999; Massarsch and Topolnicki, 2005; Topolnicki, 2004).

In Korea, site application of the DCM method has rapidly increased since its introduction in the 1980s (Jeong *et al*., 2009). Today, the DCM method is the most commonly employed ground improvement method for offshore constructions in Korea due to the nation's active national mega land reclamation and offshore development projects such as the *Sae Man Keum* reclamation (401 km^2), *Busan* new harbor, *Ulsan* new port, and *Incheon Song Do* New City reclamation (5.72 km^2). It is expected that applications of the DCM method will increase steadily due to the geographical nature of the Korean peninsula, with seas on three sides. Moreover, anticipated future active economic cooperation between South and North Korea will require numerous repair and reconstruction projects on aged harbor facilities in North Korea.

In Japan and north European countries, many studies have been conducted on the strengthening behavior, which is affected by mixing method and design type, as well as on numerical modeling, field construction technology, and QA & QC (Quality Control and Quality Assurance) concepts of the DCM method (Bruce *et al.*, 1998; Kitazume and Terashi, 2013; Porbaha, 1998; Terashi, 2002). Meanwhile, few studies on the strengthening and stability characteristics of cement treated Korean soils via experimental or numerical simulation approaches have been reported (Ahn, 2010; Shin *et al.*, 2014). Moreover, although several approaches to study the dynamic properties of natural soil have been proposed (Di Benedetto, 2007; Hardin and Drnevich, 1972; Kagawa, 1992; Kim and Stokoe, 1994; Kim *et al.*, 1991; Thiers and Seed, 1968; Vucetic and Dobry, 1991), the dynamic behavior of cement mixed and stabilized clays is almost unknown due to the lack of experimental studies.

Moreover, seismic events induced by sea waves, typhoons, tidal surges, tsunamis, or earthquakes can cause serious failures of offshore structures. For instance, the eastern Marmara earthquake (1999) caused significant damage to port and harbor facilities along the coastal area of Izmit Bay, Turkey due to failure caused by the weak seismic resistance of the subsoil (Yuksel *et al.*, 2003). Typhoon *Maemi* (September, 2003) caused serious failures and related large settlement in substituted sand and gravel deposits in Busan port, induced by the seismic load of massive waves (Cho and Kim, 2006; Kim *et al*., 2004). Foundations with stabilized soil and surrounding non-treated soft soil can be horizontally stressed by earthquake waves and sea waves, and shear strain is then increased by the shear stress generated inside the improved foundation (Finn and Fujita, 2002; Liyanapathirana and Poulos, 2005). Earthquake waves can be amplified and accelerated after passing soft soil of low density (Liyanapathirana and Poulos, 2005). Furthermore, the shear stiffness of cemented soil starts to nonlinearly decrease with shear levels of 0.001% to 1%, due to the nonlinear characteristics of the shear modulus, as also observed for natural soil (Acar and El-Tahir, 1986; Saxena *et al.*, 1988). Thus, precise evaluation of the dynamic behavior of cement treated clay is important to present reliable data for earthquake-resistant design and seismic stability analysis of DCM foundations (Sitar and Clough, 1983).

In this study, a series of experimental studies were performed to evaluate and understand the static strengthening behavior (*i.e.*, unconfined compressive strength) and dynamic geotechnical engineering properties (*i.e.*, maximum shear modulus, $G/G_{max}-\gamma$ curves, and damping ratios) of DCM-treated Korean marine clay with different curing times and cement contents.

2. Sites of Interest

Two offshore construction sites – *Ulsan* new port and *Busan* new port – where the DCM method was recently applied are considered in this study (Fig. 1).

Ulsan is an industrial city located on the southeast coast of Korea (Fig. 1; 35° 27′ *N*, 129° 3′ *E*). The rapid economic growth led by global heavy industry companies required an expansion of the city's export port. Thus, a new north breakwater has been established on the north-east shore of the city, where the new port is planned to be constructed (Fig. 2(a)). The DCM method was applied to improve a 29 m thick soft clay deposit located 21 m below the sea surface (Fig. 2(b)). The weakest top layer (1.5-4.0 m deep from the sea floor) was mixed with 330 kg/m^3 cement content to form continuous soil-cement walls with a replacement ratio higher than 98% in situ. Likewise, the middle layer (4.0 to19.0 m) and bottom layer (19.0-29.0 m) were mixed with cement content of 270 kg/m^3 and 240 kg/m^3, respectively, to represent an identical replacement ratio of 54% (Fig. 2(b)).

Busan is the biggest harbor city in Korea, located at the southeast end of the Korean peninsula (Fig. 1; 35° 08′ *N*, 128° 8′ *E*). In 2002, two breakwaters were constructed at the shore to protect a new port (Fig. 3(a)). Underlying soft clay deposits of both east and west breakwaters were improved by surcharge loading (*i.e.*, for the clay layer) and substitution (*i.e.*, sand

Fig. 1. Site of Interest. Location of Ulsan and Busan New Port

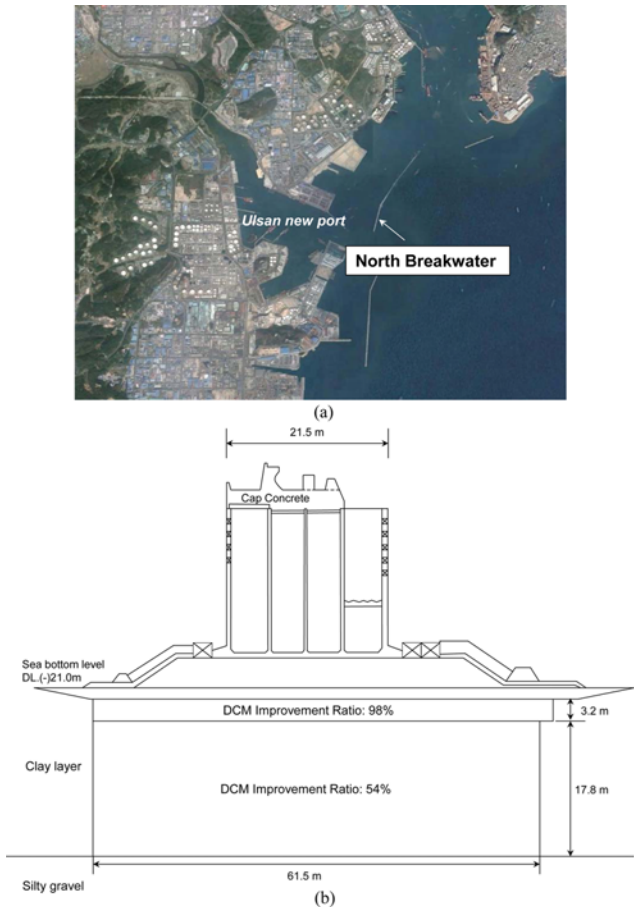


Fig. 2. Bird View and Cross Sectional Blue Print of Ulsan North Breakwater: (a) Bird View, (b) Cross Section

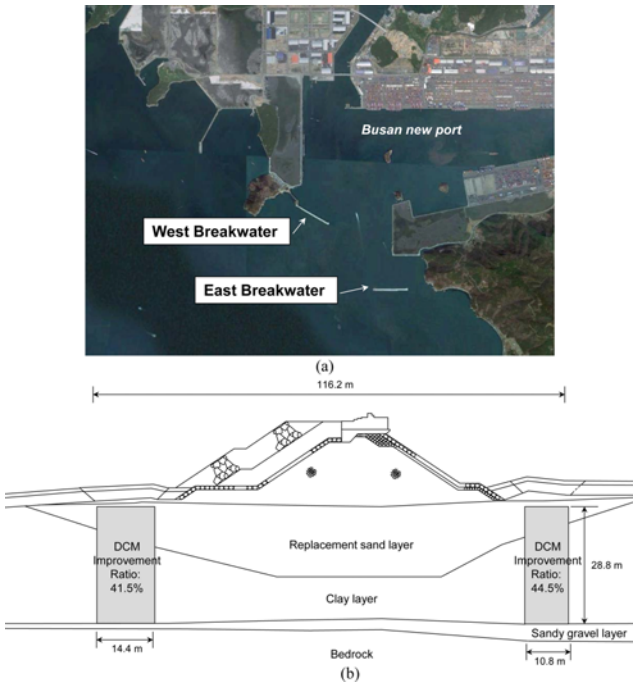


Fig. 3. Bird View and Cross Sectional Blue Print of Busan Breakwater: (a) Bird View, (b) Cross Section

replacement on the top) (Fig. 3(b)), and soil layers in front and behind the breakwater (14.0 to 43.0 m deep from the seafloor) were improved via DCM with replacement ratios of 41.5% and 44.4%, respectively, to reduce the possibilities of long-term lateral movement and associated non-uniform settlement.

3. Experimental Program

3.1 Materials Used

3.1.1 In-situ Marine Clay

Disturbed in-situ marine clays were sampled via borehole samplers from both sites of interest. In-situ geotechnical properties of both marine clays are summarized in Table 1. Detailed profiles of in-situ water content, Atterberg indices, and specific gravity are shown in Fig. 4.

Not only in-situ water content but also liquid limit and *PI* (plasticity index) of Ulsan clays are much higher than those of Busan clays, especially for shallow depths (0–20 m from seafloor), while the specific gravity of Ulsan clay is lower than that of Busan clay. Thus, it appears that the in-situ void ratio and the organic content of Ulsan clay are higher than those of Busan clay. Fig. 5 shows the clay mineral composition of typical Korean, Singaporean, and Japanese clays. Illite is the major portion among other clay minerals for Busan and Ulsan clays, while kaolinite and smectite mainly compose Singaporean and Japanese clays, respectively.

3.1.2 Cement Binder

Ordinary Portland Cement (OPC) and Blast Furnace Slag (BFS) cement are commonly used in DCM construction practices, while BFS cement is preferred over OPC due to present environmental concerns of hexavalent chromium (Cr^{6+}) emissions of OPC (Chun *et al.*, 2003). Thus, BFS cement type 2 (Eugene Koryeo Cement Co.) was used in this study, and its physical properties and chemical composition are summarized in Table 2.

3.2 Specimen Preparation

Laboratory soil-cement mixing was performed to represent

Table 1. Properties of Soft Marine Clays from Ulsan and Busan Sites

Properties	Ulsan	Busan
Specific gravity [–]	2.62	2.72
Water content [%]	90.3	73.3
Initial void ratio [–]	2.36	1.99
Total unit weight [t/m^3]	1.48	1.57
LL [%]	93.5	66.6
PI [%]	75.2	38.7
pH [–]	8.04-8.60	7.94
Organic content [%]	12.9-16.8	9.56
Cement content [kg/m^3]	240, 270, 330	150, 200, 250
	(16, 18, 22%)	(10, 13, 16%)

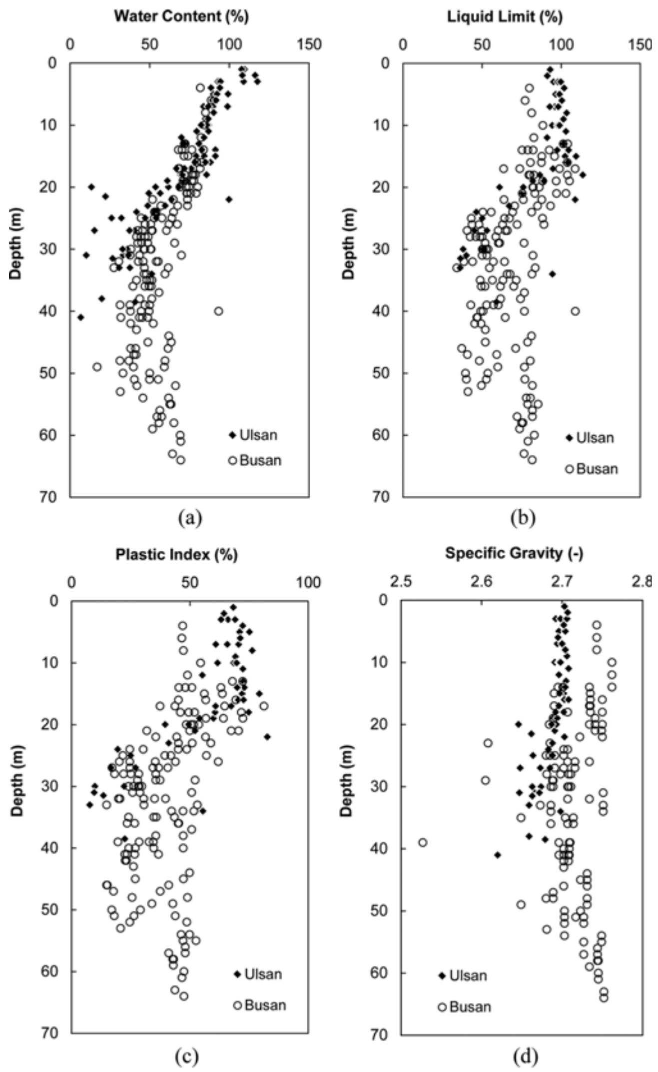
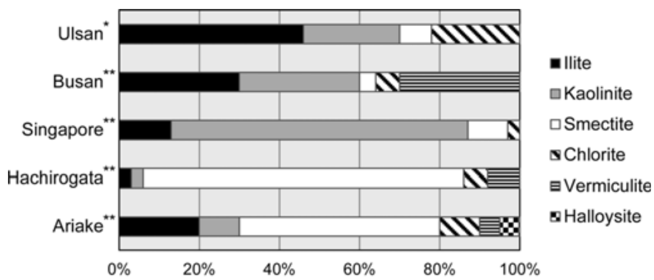


Fig. 4. Index Properties of Ulsan and Busan Marine Clays: (a) Water Content, (b) Liquid Limit, (c) Plastic Index, (d) Specific Gravity



*. Data from Min et al. (2000)
**. Data from Ohtsubo et al. (2002)

Fig. 5. Clay Mineral Proportion of Ulsan, Busan, Singapore, and Japan Clays

and evaluate geotechnical engineering parameters (*e.g.*, strength, stiffness, dynamic properties) of uniformly mixed soil-cement columns via DCM in the field. Because there are no international standards for sample preparation and experimental programs of DCM soil-cement samples in the laboratory, a number of empirical methods have been suggested by different institutions and nations, including EuroSoilStab (Stab 2002), CDIT (Coastal Development Institute of Technology (2008)), JGS (Japanese Geotechnical Society (2000)), and SGI (Swedish Geotechnical Institute (1997)) for DCM studies. In this study, cement-clay specimens were prepared by referring to JGS (2000) and KS F 2329 (2007) to obtain uniformly mixed cylindrical specimens with dimensions of 50 mm in diameter and 100 mm in height to be used for unconfined compression and resonant column tests.

Table 2. Physical Properties and Chemical Composition of Cement Binder used in this Study

	Properties	Value
Physical properties	Density [g/cm^3]	2.89-2.91
	Average grain diameter [μm]	12-16
	Specific surface [cm^2/g]	4,000-6,000
Chemical composition [%]	SiO_2	30.0-36.0
	Al_2O_3	12.0-18.0
	Fe_2O_3	0.25-0.35
	CaO	38.0-45.0
	MgO	below 10.0
	SO_3	below 4.0

Soil samples were sealed with wax to maintain their in-situ water content condition. The in-situ water contents of *Ulsan* and *Busan* marine clays were 90.3% and 73.3%, respectively. Thus, the amount of cement (kg) mixed into 1 m^3 of soil (*i.e.*, *a* in Eq. (1)) was determined by following Eqs. (1) and (2) to provide 240, 270, and 330 kg/m^3 (*i.e.*, 16, 18, and 22% to the wet weight of soil) cement-clay mixtures for *Ulsan* marine clay, as well as 150, 200, and 250 kg/m^3 (*i.e.*, 10, 13, and 16%) mixed conditions for *Busan* marine clay, which were implemented in the field equally.

$$a_c = \frac{C}{\gamma_{sat}} \times 100\,(\%) \tag{1}$$

$$W_c = W_s \times a_c \tag{2}$$

where a_c = Cement content [%]
C = Amount of cement per 1 m^3 of soil [kg/m^3]
W_c = Dry weight of cement [kg]
W_s = Weight of saturated soil [kg]
γ_{sat} = Saturated unit weight [ton/m^3]

Cement and water were mixed with w/c = 80% water to cement ratio by a laboratory cement mixer (Humboldt H-3841) for 5 minutes to obtain a uniformly mixed cement slurry similar to the real injected cement slurry in field DCM implementations. Pre-weighed soft clay was then added into the mixing bowl and mixed together with the cement slurry for 2 minutes (*i.e.*, similar to the time range for auger mixing in practice with a descending and ascending rate of 2 min/m, respectively; Fig. 6(a)) and mixing was stopped once to remove soil attached to the bowl and other unwanted locations. A second mixing was performed for

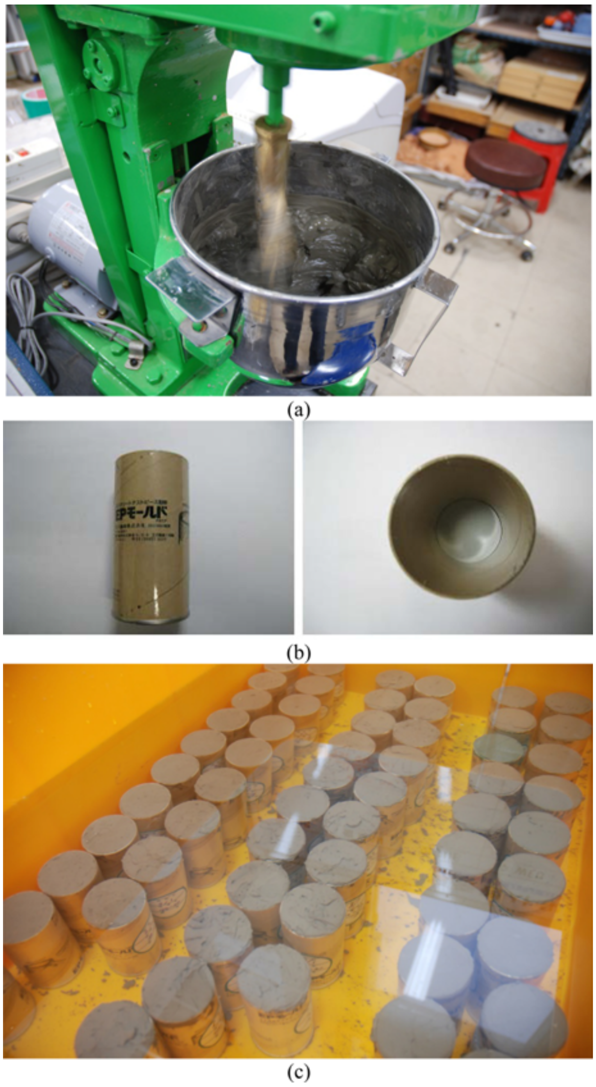


Fig. 6. DCM Sample Preparation and Laboratory Curing: (a) Soil-cement Mixing, (b) Disposable PVC Mold, (c) Curing (in water)

the same duration as the first mixing. After mixing, the mixture was poured into cylindrical PVC molds (50 mm in diameter × 100 mm in height; Fig. 6(b)). All specimens were cured in isothermal (*i.e.*, 15°C) 3.5% salt water (using bay salt) to represent the in-situ curing condition in the laboratory (Fig. 6(c)). The curing period was set to range from 1 day to 56 days in order to investigate the variation of strength and dynamic properties of cemented clay with curing time.

3.3 Unconfined Compression Test

The Unconfined Compressive Strength (UCS) of the cement treated clay was measured at 1, 3, 7, 14, 28, and 56 days of curing using an UTM (Universal Testing Machine) device (Instron 5583) with an axial strain rate of 1 mm/min (KS F 2314) (2013) up to a maximum strain of 15% (Fig. 7(a)). After specimen failure, inside fragments were collected to evaluate the water content and dry density of the cement-clay mixtures simultaneously.

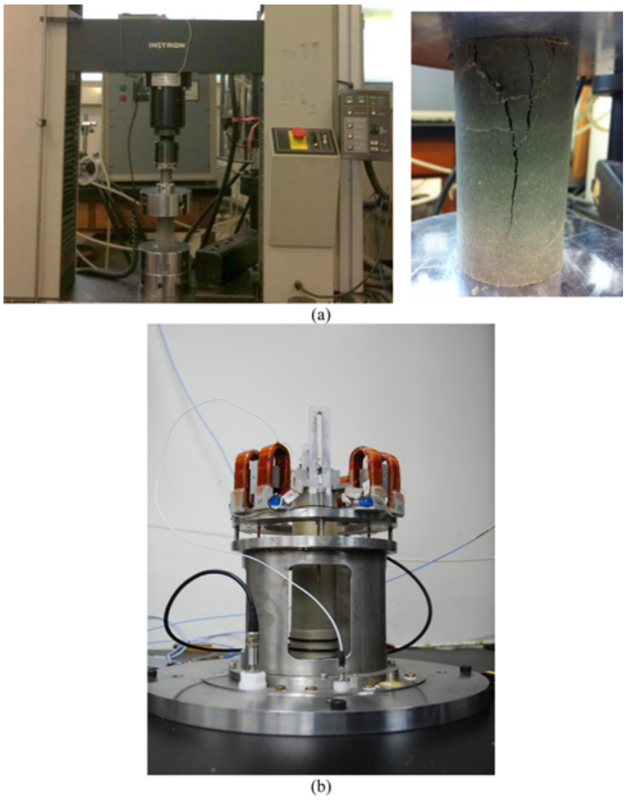


Fig. 7. Laboratory Experimental Programs: (a) Unconfined Compression Test, (b) Resonant Column (RC) Testing

Three samples were tested to obtain a reliable average value for each measurement.

3.4 Resonant Column (RC) Test

A resonant column (RC) test (Kim and Stokoe, 1994; Kim *et al*., 1991) was performed to observe the nonlinear dynamic properties (*e.g*., shear stiffness and damping) of the cement-treated clay in small-to-intermediate shear strain ranges. Torsional fixed-free type equipment was used in this study (Fig. 7(b)). The specimens were rigidly attached to both end platens by gypsum slurry (50% water to gypsum ratio in mass).

The basic operational principle is based on vibrating the cylindrical specimen in first-mode torsional motion. Applying power from 0.05 to 40 mV, the frequency of excitation was increased from a low value until the resonant frequency of the specimen was obtained. Results were used to calculate the shear wave velocity (V_s), shear modulus (G), shear strain (γ), and damping ratio (D) with equipment characteristics and size of the specimen (Drnevich *et al.*, 1978).

Previous studies (Baig *et al.*, 1997; Lovelady and Picornell, 1990) showed that the effect of confining pressure on the dynamic behavior and shear stiffness variation of cement-soil mixtures was negligible when the cement content was higher than 5%. Thus, confining pressure was not considered in this study due to the high cement contents (*i.e*., 10-22%) of the cement-clay mixtures used in this study.

4. Experimental Results and Analyses

4.1 Unconfined Compressive Strength (UCS) of Cement-treated Clay

Figure 8 provides the UCS results of cement-treated Ulsan and Busan marine clay with curing time. The strength increased sharply in the first 7 days, and slightly increased up to 28 days due to hydration and pozzolanic reactions. Meanwhile, the Busan marine clay exhibited higher strength than the Ulsan marine clay under equivalent conditions. In details, for 16% cement content to the soil mass, the Busan clay showed UCS = 4 MPa, while Ulsan clay shows UCS = 1 MPa, at 56 days of curing. The strengthening behavior of the cement-treated clay can be generally affected by natural soil properties such as natural water content, soil pH, organic content, the clay mineral (Chew *et al*., 2004; Horpibulsk *et al*., 2011; Horpibulsuk *et al.,* 2003; Tremblay *et al.*, 2002), and the molding and curing condition such as moisture content (Beckett and Ciancio, 2014; Consoli *et al.*, 2017; Osinubi *et al*., 2015) and temperature (Wang *et al.*, 2017). The higher natural water content and organic content of the Ulsan clay (Table 1) are therefore regarded as inhibiting factors on the chemical reaction of cement in situ.

4.2 Factors Affecting the Strength of Cement-treated Clays

Several relationships between the UCS and curing time of cement-treated soils have been suggested in previous studies, as summarized in Table 3. Among others, Horpibulsuk *et al.* (Horpibulsuk *et al*., 2003) provided a reliable long-term (3 to 180 days) strengthening relationship of clays as follows:

$$q_T / q_{28} = a + b \cdot \ln T \quad (3)$$

where q_T, q_{28} are the UCS at curing times of T days and 28 days, respectively, while a, b are constants.

The UCS results in Fig. 6 can be normalized by q_{28} and are displayed on a semi-logarithmic plane as Fig. 9. Both cement-treated Ulsan and Busan marine clays follow a single trend (*i.e.*, a = 0.031 and b = 0.29) with a good degree of correlation (R^2 = 0.98) regardless of cement content and the origin of soil, which is in accordance with the results of previous studies (*i.e.*, a and b constants in Table 3). Thus, it becomes possible to estimate the long-term (*i.e.*, 3 to 180 days) in-situ strength of DCM treated marine clays in the southeast coastal region of the Korean peninsula using the 28th day strength value from laboratory testing, and Eq. (3) with constants (a = 0.031 and b = 0.29) as follows:

$$q_T = q_{28}\,(0.031 + 0.29 \cdot \ln T) \quad (4)$$

4.3 Maximum Shear Stiffness of Cement-treated Clays

The maximum shear modulus values (G_{max}) of cement-mixed Ulsan and Busan marine clay specimens obtained by

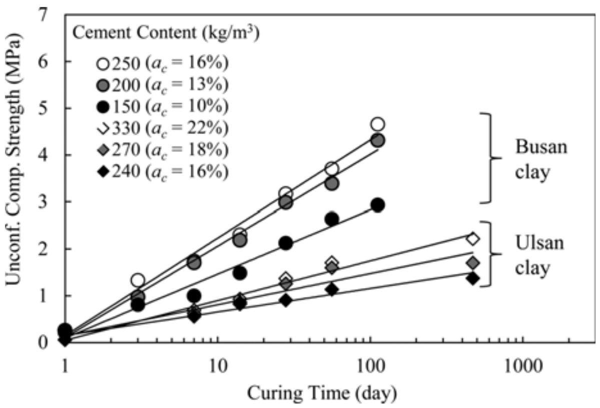


Fig. 8. Evaluation of Unconfined Compressive Strength with Curing Time

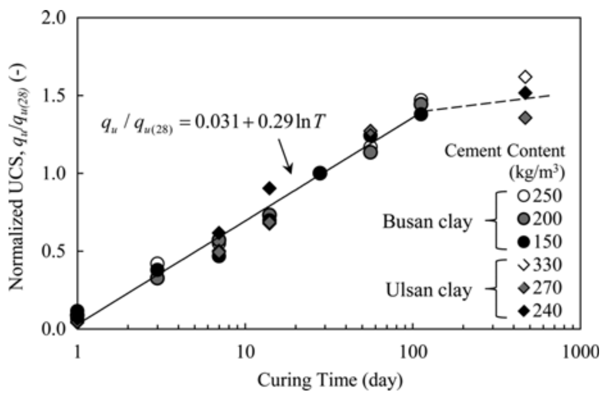


Fig. 9. Normalized Unconfined Compressive Strength ($q_u/q_{u(28)}$) with Curing Time

Table 3. Relationships between Unconfined Compressive Strength and Curing Time

Relationship	Parameter definition	Soil type	Reference
$q_{T2} = q_{T1} + K \log (T_2/T_1)$	$K = 480A_w$ $K = 70A_w$ A_w is cement content	Granular soil Fine grain soil	Mitchell *et al.* (1972)
$q_T/q_{14} = a + b \ln(T)$	a = -0.20, b = 0.458 a = 0.190, b = 0.299	Inland clays Ariake marine clays	Nagaraj and Miura (1996) Yamadera *et al.* (1998)
$q_T/q_{28} = a + b \ln(T)$	a = 0.038, b = 0.281 for LI = 1.0-2.5 a = -0.216, b = 0.342 for LI > 2.5	Bangkok clay Ariake clay	Horpibulsuk *et al.* (2003)
	a = 0.002, b = 0.294	Silty clay (fly ash blended cement)	Horpibulsuk *et al.* (2009)
	a = 0.039, b = 0.283	Kaolin clay	Horpibulsuk *et al.* (2011)

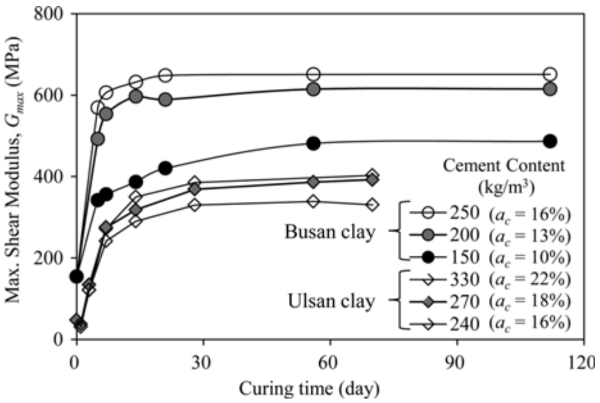


Fig. 10. Maximum Shear Modulus (G_{max}) with Curing Time

RC measurement are plotted with curing time in Fig. 10. The G_{max} increases with curing time and a higher amount of cement, while a significant increment is observed during the first 14 days and it then converges to a final value after 28 days of curing. For an equivalent amount of cement (*i.e.*, 16%), the G_{max} of Busan marine clay is almost double that of the G_{max} of Ulsan marine clay, which is in accordance with the higher compressive strength result (Fig. 8) of Busan marine clays.

Figure 11 shows the G_{max} values normalized by the G_{max} at 28 days of curing ($G_{max(28)}$) with a logarithmic time scale. The normalized strengthening (*i.e.*, shear stiffness increment) results follow a single trend during 14 days of curing, regardless of soil type and amount of cement, as follows:

$$G_{max} / G_{max(28)} = 0.12 + 0.33 \ln T. \tag{5}$$

After 14 days of curing the shear stiffness of both sites converge, while the mechanical strengthening (*i.e.*, UCS increment) continuously increases up to 96 days (Fig. 9). Fig. 11 shows that the shear stiffness increment of cement-treated clays strongly depends on the hydration reaction of cements, while the secondary pozzolanic reaction has almost no influence on the shear modulus development.

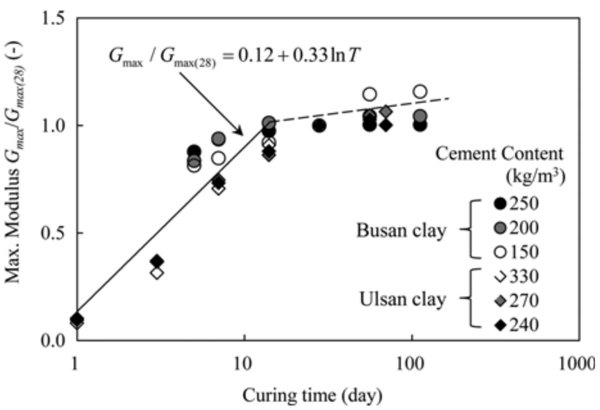


Fig. 11. Analysis of Shear Modulus Development in Cement Treated Ulsan and Busan Clay with Logarithmic Time

4.4 Strain-dependent Shear Stiffness of Cement-treated Clay

Figure 12 shows an example (270 kg/m^3 cement mixed Ulsan marine clay) of the strain dependent shear modulus variation ($G - \gamma$) of cement-treated marine clay with curing time. Regardless of the curing time, all specimens show linear behavior below 0.01% strain. However, the elastic threshold strain starts to decrease (*i.e.*, from 0.02% to lower) with curing time (Fig. 12(a)).

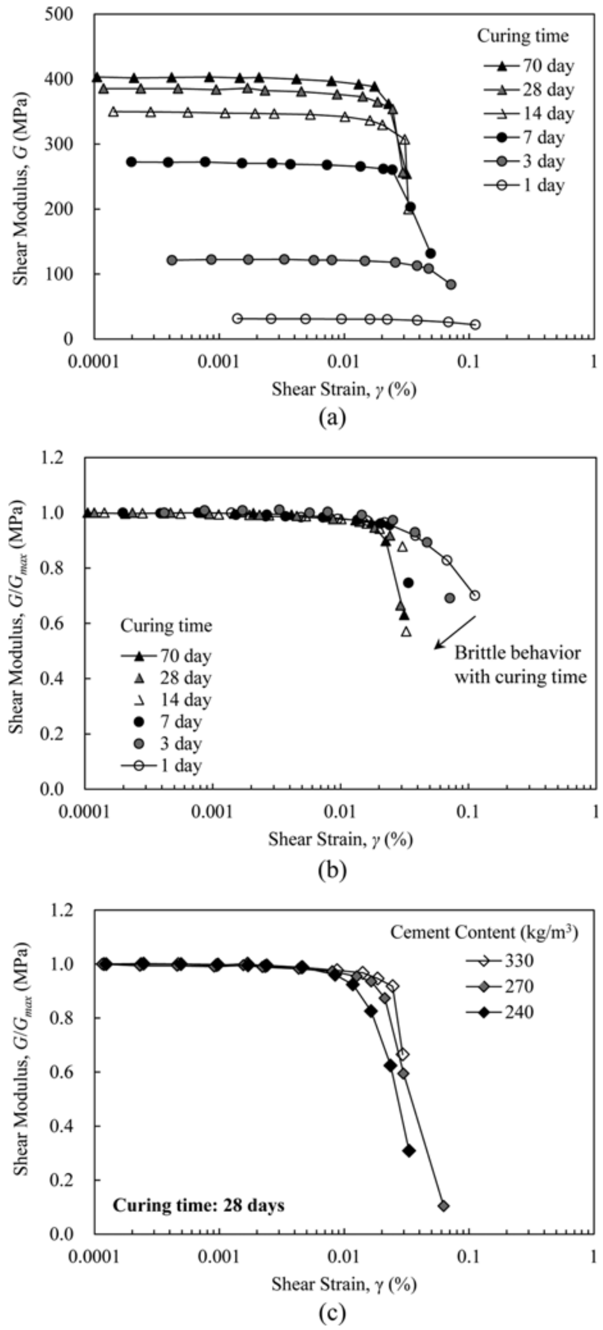


Fig. 12. Strain Dependent Shear Modulus Behavior of Ulsan Clay with Curing Time: (a) Shear Modulus (a_c = 270 kg/m^3), (b) Normalized Shear Modulus (a_c = 270 kg/m^3), (c) Normalized Shear Modulus at 28 days Curing Time (a_c = 240, 270, 330 kg/m^3)

Moreover, the normalized strain-dependent shear modulus (G/G_{max}) variation shows higher strain sensitivity (*i.e.*, strain dependent G degradation) with curing time (Fig. 12(b)), which indicates the increasing brittleness of cement-treated clays with hardening. Generally, the normalized strain-dependent shear modulus of soil increases with *PI*, friction angle, and confining pressure increase (Vucetic and Dobry, 1991), while the *PI* and ductility of cement-treated clays decreases due to the hydration reaction of cement (Balasubramaniam *et al.,* 1999; Chew *et al.*, 2004; Uddin *et al.*, 1997). Thus, the normalized strain-dependent shear modulus remarkably decreases during cement hydration, even though the G_{max} increases.

Figure 12(c) shows the effect of binder content on the strain-dependent normalized shear modulus (G/G_{max}) of Ulsan cement-treated clay at 28 days-curing time, which implies that the elastic threshold of stabilized clay depends on the cement content (*i.e.*, increases with higher binder content). This can be explained by the physico-chemical interaction between cement and pore water that welds the clay fabrics via bonding bridges (Horpibulsuk *et al.,* 2003). Thus, the number of micro-bondings increases with increasing binder content and consequently improves both the strength and stiffness of cement-mixed clays. Moreover, the decrease of ductility of cement-treated clay with increasing cement content is also accompanied by stiffer strain-dependent degradation, as shown in Fig. 12(c). Similar trends have been observed for sand specimens stabilized by very much lower cement contents of 1-4% (Acar and El-Tahir, 1986) and of 1-8% (Saxena *et al.*, 1988).

4.5 Damping Characteristics of Cement-treated Marine Clay

Generally, a material's damping ratio is expected to decrease with increasing stiffness. Thus, the damping ratio increment of cement-treated Korean southeast marine clays (Fig. 13) seems to be unreasonable at first glance. However, since the damping ratio of soil affects the energy dissipation of wave propagation through its mass, the energy required for wave propagation through a cemented soil medium should be larger than that of untreated natural soil due to the C-S-H (Calcium-Silicate Hydrates) gels formed on soil surfaces and inside the voids of cement-treated soils (Saxena *et al*., 1988). The increased brittleness of cement-treated Korean southeast coast marine clays is also observed in the damping ratio results, as shown in Fig. 13(a).

Moreover, at the same curing time (28 days), cement-treated marine clays with higher cement contents show lower damping ratio values (Fig. 13(b)), which is in accordance with the finding that higher cement ratios induce connections of C-S-H gels in soil to become more brittle (Balasubramaniam *et al*., 1999; Chew *et al.*, 2004; Uddin *et al*., 1997). Similar damping behaviors of cemented sand have been also reported by Acar *et al.* (Acar and El-Tahir, 1986) and Saxena et al. (Saxena *et al*., 1988). Thus, the damping ratio behaviors of cement-treated Korean marine clays can be cautiously concluded to provide the appropriate seismic resistance in practice.

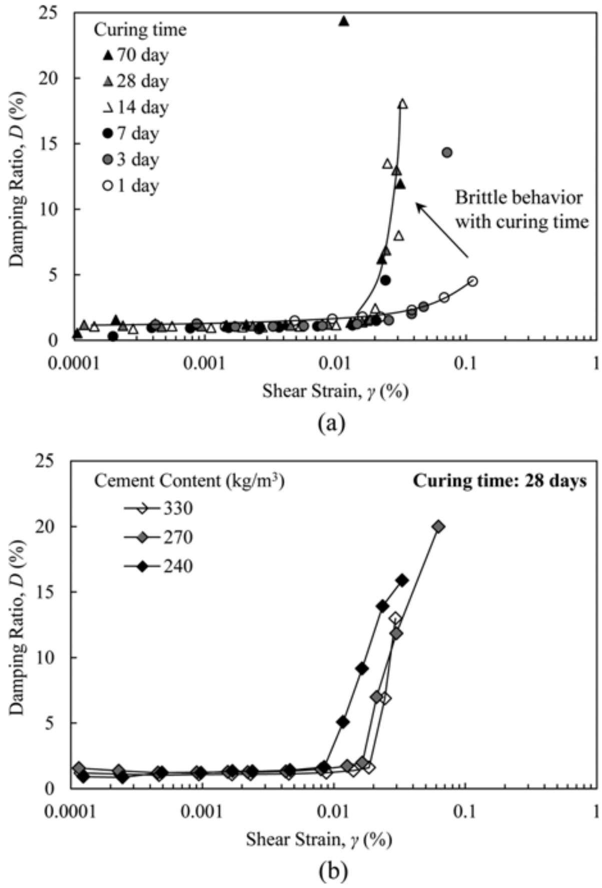


Fig. 13. Strain Dependent Damping Characteristic of Ulsan Clay: (a) Variation of Damping Ratio with Curing Time (a_c = 270 kg/m^3), (b) Damping Ratio at 28 days Curing Time (a_c = 240, 270, 330 kg/m^3)

4.6 Correlation between Shear Stiffness and Strength

In practice, three methods are commonly used to conduct tests of the shear stiffness of soils in situ: (1) field seismic survey (*e.g.*, shear wave velocity); (2) laboratory experiments (*e.g.*, Resonant column test, dynamic triaxial test); and (3) estimation via empirical equations, when both field and laboratory attempts are impossible or restricted. From this study, experimental results of both unconfined compression test and RC test show correlation between normalized G_{max} ($G_{max}/G_{max(28)}$) and normalized UCS ($q_u/q_{u(28)}$) as represented in Fig. 14 and follow:

$$G_{\max} / G_{\max(28)} = 0.287 \ln(q_u / q_{u(28)}) + 1 \tag{6}$$

Thus, it becomes possible to predict the in-situ G_{max} values of Korean marine clays regardless of time, using only their static state UCS values and 28 days-shear stiffness (G_{28}).

In previous studies, the ratio of shear stiffness to UCS (*i.e.*, G/q_u) of DCM marine clays has been estimated as 50-200 without dynamic approaches, but just considering linear elasticity of cement-clay mixtures with E/q_u ratios, and shear modulus assumptions (*i.e.*, $G = 0.5 \cdot E/(1 + \nu)$; ν = 0.3~0.5) (Asano *et al.,* 1996; Futaki *et al.*, 1996; Lee *et al*., 2005). However, in this study the UCS of cement-mixed Korean marine clays increased

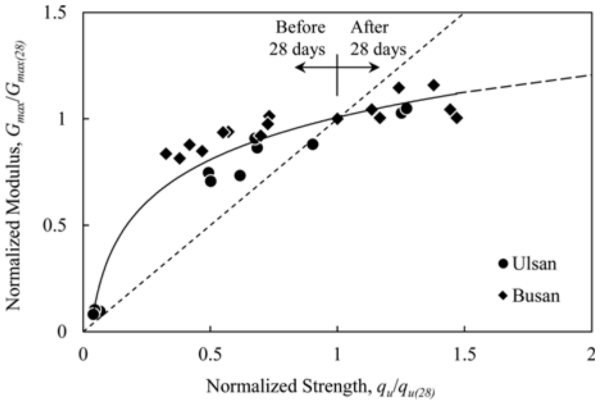


Fig. 14. Relationship between Shear Modulus and Unconfined Compressive Strength Normalized by Normalized by 28 days-values, Respectively

continuously up to 120 days (Fig. 8), while shear moduli rapidly increased during the first 14 days and converged afterwards (Fig. 10). This indicates that the shear modulus of the cement-treated Korean marine clay can be predicted using the suggested correlation obtained from the experimental tests within a curing period of 112 days. It should be noted that the suggested correlation was verified only for two types of clay (*i.e.*, Ulsan and Busan clay). Therefore, further investigations of various clay types, binder types, and water-cement ratios are recommended for enhanced generalization.

5. Discussion

The UCS of cement-treated Korean marine clay obviously increases with curing time and higher cement content (Fig. 8). Under equivalent binder content conditions, the strength of Busan marine clay was four times higher than that of Ulsan marine clay, which seems to be affected by the higher water and organic contents of the Ulsan clay. In general, the strength development behavior of cement-treated clay is governed by several properties of soft clay. The mineralogy of soft clay, in particular, has a significant influence on the strength development of cement-treated clay, because the cation exchange capacity (CEC; cation exchange between Ca^{2+} of cement hydrates and clay minerals) differs among different clay mineral types (Chapman, 1965).

The CEC of illite (10-40 meq/100 g) (Carroll, 1959) and kaolinite (3-15 meq/100 g) (Carroll, 1959) are reported to be lower than that of smectite (60-120 meq/100 g) (Schiffman and Southard, 1996). The smectite is a dominant mineral for Japanese clay, while illite and kaolinite consist more than 50% in Korean marine clay (Fig. 5). Therefore, the 28 days-strength of cement-treated Korean marine clay is relatively smaller than that of Japan Ariake clay (Horpibulsuk *et al*., 2003) but higher than that of Singapore clay (Chew *et al*., 2004) under similar mixing conditions (*i.e.* initial water content, water-cement ratio, cement content) because the smectite fraction of Japanese clay is much higher than that of Korean and Singapore marine clays. Even though the values of 28 days-strength are different for each kind of soft clay, the overall strengthening behavior normalized by the strength of 28 days of curing can be represented as a logarithmic correlation, which is similar with the results (*i.e.* Bangkok clay, Ariake clay, Thailand clay, kaolin clay) from previous studies (Horpibulsk *et al*., 2011; Horpibulsuk *et al*., 2003; Liu *et al*., 2008; Mitchell *et al*., 1972; Nagaraj and Miura, 1996; Yamadera *et al.,* 1998).

The maximum shear modulus values (G_{max}) of cement-mixed Ulsan and Busan marine clays increased significantly during the first 14 days and then converged after 28 days of curing (Fig. 10), while the strength increased almost continuously over a hundred days of curing time (Fig. 8). Micro-bonding via cement hydrates, which welds each clay particle, is generated directly around clay particles and increases rapidly during the early stage of curing. After the clay particles have been enclosed by micro-bonding, the cementitious product generated by hydration and pozzolanic reactions fills the pores of the cement-mixed clay or thickens the micro-bonds. Therefore, the micro-scale properties (*i.e.*, shear stiffness) increase sharply during early curing and then almost converge, while the macro-properties (*i.e.*, strength) increase consistently until the end of the pozzolanic reaction. Moreover, these formation characteristics of micro-bonding in clayey soil influence the strain-dependent behavior (*i.e.* normalized shear modulus, damping ratio; Figs. 12 & 13) because water molecules surrounding the clay particles are almost depleted, which reduces the *PI* of cement-mixed clays.

6. Conclusions

In this study, a series of laboratory experiments were performed to evaluate the static strengthening and dynamic behaviors and geotechnical engineering design parameters of DCM treated Korean marine clays. Unconfined compression tests and Resonant Column (RC) tests were performed on cement-clay mixtures prepared in the laboratory with 10-22% cement contents and 80% water to cement ratio mixing conditions.

The Unconfined Compressive Strength (UCS) of cement-treated marine clay specimens obviously increases with cement content and increased curing time. In detail, the UCS increases sharply during the early stage due to the cement hydration reaction, and then subsequently increases slightly via secondary pozzolanic reactions. The trends of strength development normalized by 28 days-strength (q_{28}) can be represented in a logarithmic correlation, which is in accordance with previous studies, regardless of cement content and clay type. The strength of Busan marine clay is four times higher than that of Ulsan marine clay for an equivalent cement to soil ratio in mass, which is attributed to the higher in-situ water and organic contents of Ulsan clay. In addition, the q_{28} of cement-treated Korean marine clay is relatively smaller than the q_{28} of Japanese clay under similar mixing conditions due to the different site-specific clay mineral fraction.

The maximum shear modulus (G_{max}) of DCM treated Korean marine clays increases with curing time and higher cement contents, and rapidly increases during the first 14 days of curing and then converges thereafter. For equivalent cement to soil content in mass, the shear stiffness of Busan marine clay is almost double the shear stiffness of Ulsan marine clay, which is in accordance with the higher UCS behavior. The shear stiffness increment normalized by 28 days-shear stiffness (G_{28}) represents a single trend, regardless of the in-situ soil type and binder content used for DCM implementation.

The normalized shear stiffness variation (G/G_{max}) of DCM treated Korean marine clays shows higher strain sensitivity (*i.e.*, strain dependent G degradation) with curing time and increasing cement content, which indicates higher brittleness of cement-treated clays due to a reduction in PI as a result of the hydration reaction of the cement. The increased brittleness is also observed in the damping ratio behavior of cement treated clay specimens. At 28 days of curing, specimens mixed with higher cement contents showed lower damping ratio values, which implies that higher cement content induces more connections of C-S-H gels between clay particles, which become more brittle.

This study not only provided evaluations of the geotechnical engineering behaviors of cement-treated Korean marine clays, but also analyzed the dynamic properties of soft clays mixed with a high cement content of over 15%, which has not previously been investigated by other researchers. Findings from this study can be effectively used to evaluate the static and dynamic stability of DCM-treated soft clay. However, it is noted that this study does not consider binder type, water-cement ratio, or salinity of pore water because the conditions used for the preparation of the cement-mixed specimens, and the experimental tests, were performed in accordance with the *in-situ* field conditions. As such, further studies are needed to generalize the complicated geotechnical engineering behaviors of DCM-treated clays and to widely apply the correlations suggested in this study.

Acknowledgements

This research was supported by the development of design and construction technology for the Deep Cement Mixing (DCM) method at Samsung C&T Engineering and Construction Group.

References

Acar, Y. B. and El-Tahir, E.-T. A. (1986). “Low strain dynamic properties of artificially cemented sand.” *Journal of Geotechnical Engineering*, Vol. 112, No. 11, pp. 1001-1015, DOI: 10.1061/(ASCE)0733-9410(1986)112:11(1001).

Ahn, T. B. (2010). “Effects of DCM column properties in softground on stabilities of underground roadway.” *KSCE Journal of Civil Engineering*, Vol. 30, No. 2C, pp. 77-84.

Asano, J., Ban, K., Azuma, K., and Takahashi, K. (1996). “Deep mixing method of soil stabilization using coal ash.” *Proc., Proceedings of the 2nd International Conference on Ground Improvement Geosystems, Grouting and Deep Mixing*, pp. 393-398.

Baig, S., Picornell, M., and Nazarian, S. (1997). “Low strain shear moduli of cemented sands.” *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 6, pp. 540-545, DOI: 10.1061/(ASCE) 1090-0241(1997)123:6(540).

Balasubramaniam, A., Lin, D., Sharma Acharya, S., Kamruzzaman, A., Uddin, K., and Bergado, D. (1999). “Behavior of soft Bangkok clay treated with additives.” *A. A. Balkema, P. O. Box 1675 NL-3000 BR Rotterdam The Netherlands.*, pp. 11-14.

Beckett, C. and Ciancio, D. (2014). “Effect of compaction water content on the strength of cement-stabilized rammed earth materials.” *Can. Geotech. J.*, Vol. 51, No. 5, pp. 583-590.

Bruce, D. A., Bruce, M. E. C., and DiMillio, A. F. (1998). “Deep mixing method: A global perspective.” *Civil Engineering*, Vol. 68, No. 12, pp. 1-26.

Carroll, D. (1959). “Ion exchange in clays and other minerals.” *Geological Society of America Bulletin*, Vol. 70, No. 6, pp. 749-779, DOI: 10.1130/0016-7606(1959)70[749:IEICAO]2.0.CO;2.

Chapman, H. (1965). “Cation-exchange capacity.” *Methods of soil analysis. Part 2. Chemical and microbiological properties* (methodsofsoilanb), pp. 891-901.

Chew, S., Kamruzzaman, A., and Lee, F. (2004). “Physicochemical and engineering behavior of cement treated clays.” *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 7, pp. 696-706, DOI: 10.1061/(ASCE)1090-0241(2004)130:7(696).

Cho, Y. S. and Kim, H. J. (2006). “Sea level change due to typhoons in Korean peninsula.” *Journal of coastal research*, Vol. 22, No. 3, pp. 678-682, DOI: 10.2112/04-0269.1.

Chun, B. S., Lee, J. Y., and Seo, D. D. (2003). “The injection characteristics and environmental effects for grouting materials based on cement.” *Journal of the Korean Geotechnical Society*, Vol. 19, No. 2, pp. 159-170.

Coastal Development Institute of Technology (2008). “Technical manual for deep mixing with reference to marine works (Revised version).” Tokyo.

Cokca, E. (2001). “Use of class c fly ashes for the stabilizationof an expansive soil.” *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 7, pp. 568-573, DOI: 10.1061/(ASCE) 1090-0241(2001)127:7(568).

Consoli, N. C., Quiñónez, R. A., González, L. E., and López, R. A. (2016). “Influence of molding moisture content and porosity/cement index on stiffness, strength, and failure envelopes of artificially cemented Fine-Grained soils.” *Journal of Materials in Civil Engineering*, 04016277, DOI: 10.1061/(ASCE)MT.1943-5533.0001819.

Consoli, N. C., Winter, D., Rilho, A. S., Festugato, L., and D. S. Teixeira, B. (2015). “A testing procedure for predicting strength in artificially cemented soft soils.” *Engineering Geology*, Vol. 195, pp. 327-334.

Di Benedetto, H. (2007). “Small strain behaviour and viscous effects on sands and sand-clay mixtures.” *Soil Stress-Strain Behavior: Measurement, Modeling and Analysis*, Springer, pp. 159-190.

Drnevich, V., Hardin, B., and Shippy, D. (1978). “Modulus and damping of soils by the resonant-column method.” *Dynamic geotechnical testing*, ASTM International.

EuroSoilStab (2002). “Development of design and construction methods to stabilize soft organic soils: Design Guide for soft soil stabilization.” *CT97-0351, European Commission, Industrial and Materials Technologies Programme (Rite-EuRam III) Bryssel*.

Finn, W. D. L. and Fujita, N. (2002). “Piles in liquefiable soils: seismic analysis and design issues.” *Soil Dynamics and Earthquake Engineering*, Vol. 22, Nos. 9-12, pp. 731-742, DOI: 10.1016/S0267-7261(02) 00094-5.

Futaki, M., Nakano, K., and Hagino, Y. (1996). “Design strength of soil cement columns as foundation ground for structures." *Proc., Grouting and Deep Mixing Conference, Tokyo*, pp. 481-484.

Hardin, B. O. and Drnevich, V. P. (1972). "Shear modulus and damping in soils: Measurement and parameter effects." *Journal of Soil Mechanics & Foundations Div*, Vol. 98, No. 6, pp. 603-624.

Holm, G. (2001). "Deep Mixing." *Soft Ground Technology*, pp. 105-122.

Horpibulsk, S., Rachan, R., Suddeepong, A., and Chinkulkijniwat, A. (2011). "Strength development in cement admixed Bangkok clay: Laboratory and field investigations." *Soils and Foundations*, Vol. 51, No. 2, pp. 239-251, DOI: 10.3208/sandf.51.239.

Horpibulsuk, S., Miura, N., and Nagaraj, T. (2003). "Assessment of strength development in cement-admixed high water content clays with Abrams' law as a basis." *Geotechnique*, Vol. 53, No. 4, pp. 439-444, DOI: 10.1680/geot.2003.53.4.439.

Horpibulsuk, S., Rachan, R., and Raksachon, Y. (2009). "Role of fly ash on strength and microstructure development in blended cement stabilized silty clay." *Soils and Foundations*, Vol. 49, No. 1, pp. 85-98, DOI: 10.3208/sandf.49.85.

Japanese Geotechnical Society (2000). *Practice for Making and Curing Stabilized Soil Specimens without Compaction*, Tokyo, Japan.

Jeong, G. H., Shin, M. S., Han, G. T., Kim, J. H., and Kim, Y. S. (2009). "DCM Application to south breakwater foundation in ulsan new port." *International Symposium on Deep Mixing & Admixture Stabilization*, Okinawa, Japan.

Kagawa, T. (1992). "Moduli and damping factors of soft marine clays." *Journal of Geotechnical Engineering*, Vol. 118, No. 9, pp. 1360-1375, DOI: 10.1061/(ASCE)0733-9410(1992)118:9(1360).

Kezdi, A. (1979). "Stabilized earth roads, Development in Geotechnical Engineering." *Elseviver Company.*

Kim, D. H., Oh, B. C., Han, S. H., Shim, J. S., Chun, I. S., Song, M. S., and Jo, J. S. (2004). "Collapse of container cranes at busan ports under typhoon maemi." *Proc., The Fourteenth International Offshore and Polar Engineering Conference*, International Society of Offshore and Polar Engineers.

Kim, D. S. and Stokoe, K. H. (1994). "Torsional motion monitoring system for Small-Strain (10−5 to 10−3%) soil testing." *Geotechnical Testing Journal*, Vol. 17, No. 1, pp. 17-26, DOI: 10.1520/GTJ10068J.

Kim, D. S., Stokoe, K. H., and Hudson, W. R. (1991). *Deformational characteristics of soils at small to intermediate strains from cyclic tests*, Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin.

Kitazume, M. and Terashi, M. (2013). *The deep mixing method*, CRC Press.

Korean Standard Association (2007). "Testing method for making curing of soil-cement compression and flexure test specimens in the laboratory (KS F 2329)."

Korean Standard Association (2013). "Standard test method for unconfined compression test of soils (KS F 2314)."

Lee, F. H., Lee, Y., Chew, S. H., and Yong, K. Y. (2005). "Strength and modulus of marine clay-cement mixes." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 2, pp. 178-186, DOI: 10.1061/(ASCE)1090-0241(2005)131:2(178).

Lin, K. Q. and Wong, I. H. (1999). "Use of deep cement mixing to reduce settlements at bridge approaches." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 125, No. 4, pp. 309-320, DOI: 10.1061/(ASCE)1090-0241(1999)125:4(309).

Liu, S., Zhang, D., Liu, Z., and Deng, Y. (2008). "Assessment of unconfined compressive strength of cement stabilized marine clay." *Marine Georesources and Geotechnology*, Vol. 26, No. 1, pp. 19-35, DOI: 10.1080/10641190801937916.

Liyanapathirana, D. S. and Poulos, H. G. (2005). "Pseudostatic approach for seismic analysis of piles in liquefying soil." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 12, pp. 1480-1487, DOI: 10.1061/(ASCE)1090-0241(2005)131:12(1480).

Lovelady, P. L. and Picornell, M. (1990). "Sample coupling in resonant column testing of cemented soils." *Dynamic elastic modulus measurements in materials*, ASTM International, DOI: 10.1520/STP24624S.

Maher, M. H. and Ho, Y. C. (1994). "Mechanical properties of Kaolinite/Fiber soil composite." *Journal of Geotechnical Engineering*, Vol. 120, No. 8, pp. 1381-1393, DOI: 10.1061/(ASCE)0733-9410(1994)120:8(1381).

Massarsch, K. and Topolnicki, M. (2005). "Regional report: European practice of soil mixing technology." *Proc., Proc. of Int. Conference on Deep Mixing–Best Practice and Recent Advances, Stockholm*, R19-R45.

Mitchell, J. K., Ueng, T., and Monismith, C. (1972). "Behavior of stabilized soils under repeated loading." *Performance evaluation of Cement-Stabilized soil layers and its relationship to pavement design*, No. 3-145 Contr Rpt. 1972.

Nagaraj, T. and Miura, N. (1996). "Induced cementation of soft ground—A parametric assessment." *Proc., Proc. Int. Symp. on Lowland Technology, Saga Univ., Japan*, pp. 85-97.

Nicholson, P. G. (2014). *Soil improvement and ground modification methods*, Butterworth-Heinemann.

Osinubi, K. J., Moses, G., Oriola, F. O. P., and Liman, A. S. (2015). "Influence of molding water content on shear strength characteristic of compacted cement kiln dust treated lateritic soils for liners and covers." *Niger. J. Technol.*, Vol. 34, No. 2, pp. 266-271.

Porbaha, A. (1998). "State of the art in deep mixing technology: Part I. Basic concepts and overview." *Proceedings of the Institution of Civil Engineers-Ground Improvement*, Vol. 2, No. 2, pp. 81-92.

Quigley, R. M. (1980). "Geology, mineralogy, and geochemistry of Canadian soft soils: A geotechnical perspective." *Canadian Geotechnical Journal*, Vol. 17, No. 2, pp. 261-285, DOI: 10.1139/t80-026.

Saxena, S. K., Avramidis, A. S., and Reddy, K. R. (1988). "Dynamic moduli and damping ratios for cemented sands at low strains." *Canadian Geotechnical Journal*, Vol. 25, No. 2, pp. 353-368, DOI: 10.1139/t88-036.

Schaefer, V. R., Abramson, L. W., Drumheller, J. C., and Sharp, K. D. (1997). "Ground improvement, ground reinforcement and ground treatment: Developments 1987-1997." ASCE. 1997.

Schiffman, P. and Southard, R. (1996). "Cation exchange capacity of layer silicates and palagonitized glass in mafic volcanic rocks: A comparative study of bulk extraction and in situ techniques." *Clays and Clay Minerals*, Vol. 44, No. 5, pp. 624-634.

Shin, H. Y., Kim, B. I., Kim, K. O., and Han, S. J. (2014). "A comparative study of structural analysis on DCM improved by pile and block type." *Journal of the Korean Geotechnical Society*, Vol. 30, No. 4, pp. 5-19, DOI: 10.7843/kgs.2014.30.4.5.

Sitar, N. and Clough, G. W. (1983). "Seismic response of steep slopes in cemented soils." *Journal of Geotechnical Engineering*, Vol. 109, No. 2, pp. 210-227, DOI: 10.1061/(ASCE)0733-9410(1983)109:2(210).

Swedish Geotechnical Society (1997). *Lime and Lime Cement Columns: Guide for Project Planning, Construction and Inspection*.

Terashi, M. (2003). "The state of practice in deep mixing methods." *Proc., Grouting and ground treatment*, ASCE, pp. 25-49.

Thiers, G. R. and Seed, H. (1968). "Cyclic stress-strain characteristics of clay." *Journal of Soil Mechanics & Foundations Div*, Vol. 94, No. sm2, pp. 555-569.

Topolnicki, M. (2004). "In situ soil mixing." *Ground Improvement* 2nd edition, Moseley, M. P. & Kirsch, K., Editors, Spon Press, New York, NY, USA, pp. 331-428.

Tremblay, H., Duchesne, J., Locat, J., and Leroueil, S. (2002). "Influence of the nature of organic compounds on fine soil stabilization with cement." *Canadian Geotechnical Journal*, Vol. 39, No. 3, pp. 535-546, DOI: 10.1139/t02-002.

Uddin, K., Balasubramaniam, A., and Bergado, D. (1997). "Engineering behavior of cement-treated Bangkok soft clay." *Geotechnical Engineering*, Vol. 28, pp. 89-119.

Vucetic, M. and Dobry, R. (1991). "Effect of soil plasticity on cyclic response." *Journal of Geotechnical Engineering*, Vol. 117, No. 1, pp. 89-107, DOI: 10.1061/(ASCE)0733-9410(1991)117:1(89).

Wang, D., Zentar, R., and Abriak, N. E. (2017). "Temperature-Accelerated strength development in stabilized marine soils as road construction materials." *Journal of Materials in Civil Engineering*, 0401628, DOI: 10.1061/(ASCE)MT.1943-5533.0001778.

Yamadera, A., Nagaraj, T., and Miura, N. (1998). "Prediction of strength development in cement stabilized marine clay." *Proc., Proceedings of the Geotechnical Engineering Conference, Bangkok, Thailand*, pp. 141-153.

Yuksel, Y., Alpar, B., Yalciner, A. C., Cevik, E., Ozguven, O., and Celikoglu, Y. (2003). *Effects of the eastern Marmara earthquake on marine structures and coastal areas*, Telford, London, ROYAUME-UNI.