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/Gmax 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 al., 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: kimaram@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 Saemangeum reclamation (401 km²), Busan new harbor, Ulsan new port, and Incheon Songdo New City reclamation (5.72 km²). 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 (Yüksel 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-resilient 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} – γ 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/m³ cement content to form continuous soil-cement walls with a replacement ratio higher than 98% in situ. Likewise, the middle layer (4.0 to 19.0 m) and bottom layer (19.0-29.0 m) were mixed with cement content of 270 kg/m³ and 240 kg/m³, 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](image-url)
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
Ah-Ram Kim, Ilhan Chang, Gye-Chun Cho, and Seong-Hyeon Shim

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.

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.

$$W_c = W_s \times \frac{a}{\gamma_{sat}} \times 100(\%) \quad (1)$$

$$W_r = W_i \times a_c \quad (2)$$

where

- $a_c$ = Cement content [%]
- $C$ = Amount of cement per 1 m$^3$ of soil [kg/m$^3$]
- $W_i$ = Dry weight of cement [kg]
- $W_r$ = Weight of saturated soil [kg]
- $\gamma_{sat}$ = 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-weighted 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...
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.

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 ($\gamma$), 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; Horpibulsuk 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:

\[ \frac{q_T}{q_{28}} = a + b \ln(T) \]  

(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., \( a, b \) 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:

\[ q_T = q_{28} (0.031 + 0.29 \ln T) \]  

(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
RC measurement are plotted with curing time in Fig. 10. The $G_{\text{max}}$ 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 $G_{\text{max}}$ of Busan marine clay is almost double that of the $G_{\text{max}}$ of Ulsan marine clay, which is in accordance with the higher compressive strength result (Fig. 8) of Busan marine clays.

Figure 11 shows the $G_{\text{max}}$ values normalized by the $G_{\text{max}}$ at 28 days of curing ($G_{\text{max}(28)}$) 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:

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

(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.

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. 10. Maximum Shear Modulus ($G_{\text{max}}$) with Curing Time](image)

![Fig. 11. Analysis of Shear Modulus Development in Cement Treated Ulsan and Busan Clay with Logarithmic Time](image)

![Fig. 12. Strain Dependent Shear Modulus Behavior of Ulsan Clay with Curing Time](image)
Moreover, the normalized strain-dependent shear modulus \(G/G_{\text{max}}\) variation shows higher strain sensitivity \((i.e., \text{strain dependent } G \text{ degradation})\) 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 \(G_{\text{max}}\) increases.

Figure 12(c) shows the effect of binder content on the strain-dependent normalized shear modulus \(G/G_{\text{max}}\) of Ulsan cement-treated clay at 28 days-curing time, which implies that the elastic threshold of stabilized clay depends on the cement content \((i.e., \text{increases with higher binder content})\). 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 (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.

### 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 \((e.g., \text{shear wave velocity})\); (2) laboratory experiments \((e.g., \text{Resonant column test, dynamic triaxial test})\); 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 \(G_{\text{max}}\) \((G_{\text{max}}/G_{\text{max}(28)}\) and normalized UCS \((q_u/q_{u(28)})\) as represented in Fig. 14 and follow:

\[
G_{\text{max}} / G_{\text{max}(28)} = 0.287 \ln(q_u / q_{u(28)}) + 1
\]

Thus, it becomes possible to predict the in-situ \(G_{\text{max}}\) 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 \((i.e., G = 0.5E/(1 + v); v = 0.3~0.5)\) (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.
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 marine clay is much higher than that of Korean and Singaporean 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 (Horpibulsuk 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 ($G_{	ext{max}}$) 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 ($G_{	ext{max}}$) 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<sub>max</sub>) 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<sub>max</sub>) 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


cement columns as foundation ground for structures.” Proc., Grouting and Deep Mixing Conference, Tokyo, pp. 481-484.


