Laboratory and Field Simulations on the Compression Behavior of Reinforced Soil-Cement Pile for Deep Ground Improvement Application

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ABSTRACT

Deep Mixing Method (DMM) is an effective ground improvement technique which improves the geotechnical properties of thick deposit of weak soils by introducing some cementitious materials into and within the soil deposit. This paper proposes a new soil improvement method that employs reinforced deep mixing method (RDMM). In the RDMM, the deep mixing pile is reinforced in a manner similar to a spirally reinforced concrete column or pile. This paper aims to evaluate the effectiveness of RDMM on improving the strength and deformation properties of a non-plastic soil. The study comprises of four (4) experimental phases, namely: 1) physical property tests of the base soil, (2) Unconfined Compression (UC) tests on unreinforced cement-admixed soil specimens, (3) UC Tests on reinforced cement-admixed soil specimens, and (4) construction and load testing of full-scale RDMM pile. Results of UC tests on reinforced cement-admixed soil revealed that the cement content (A_w), number of longitudinal bars (n_b) and spacing of spiral (SS) reinforcement have significant contributions on the strength gain of reinforced cement-admixed non-plastic soil. The results of UC tests further revealed that the influence of longitudinal bars on the unconfined compressive strength of reinforced cement-admixed non-plastic soil is pronounced at lower cement contents. Furthermore, static load test conducted on the full-scale RDMM pile revealed the load-settlement behavior of single RDMM pile.

Keywords: **deep mixing method, RDMM pile, cement-admixed soil, non-plastic soil**

I. INTRODUCTION

Growing population and rising standards of living have resulted in the increasing demands of urban infrastructure. The increasing demand of urban infrastructure has led to land shortages. In the Philippines, especially in urbanized areas, the chances to have good quality construction sites become rarer and it is necessary to consider sites that include problematic soils. Solutions for development on these problematic sites involved either soil improvement techniques or deep foundation systems.

Deep mixing method (DMM) is a soil/ ground improvement technique that mixes reagents into the soil at a specific depth to improve the in-situ soil properties without requiring excavation or removal. Binders, such as lime or cement are mixed with the soil by rotating mixing tools and can be introduced in dry or slurry form. The stabilized soil, often produced soil-cement pile, has higher strength, lower compressibility, and lower permeability than the native soil. Methods of mixing generally applied in the installation of deep mixing piles are either mechanical mixing or high pressure jet mixing [1, 2]. This paper proposed a new soil improvement called reinforced deep mixing method (RDMM). In this method, the deep mixing pile is reinforced with deformed steel bars. The addition of reinforcing bars is expected to increase the stiffness and load carrying capacity of soil-cement pile. Furthermore, the lateral confinement provided by the spiral reinforcement is expected to increase the strength and control the deformation of deep mixing pile. RDMM pile can be used as structural members to resist vertical loads as well as lateral load. If proven effective, RDMM can be used as pile foundation for lightly loaded structures in lieu of existing concrete piles. RDMM has several advantages over the existing concrete piles in terms of construction and economy because it uses native soil as aggregates. Concrete, steel or timber piles when used as friction piles are considered over-strength because friction piles derive their bearing capacity mainly from the skin friction or adhesion between the pile and the surrounding soil. Thus, the axial capacity of pile is not fully utilized during the service load because a bigger portion of the load is carried by

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the shaft resistance. The strength of these piles is normally utilized in handling and driving operation during the construction [3].

II. METHODS AND MATERIALS

The Base Soil

The base soil used in this study was taken inside the campus of Mindanao State University -Iligan Institute of Technology (MSU-IIT), Tibanga, Iligan City Philippines. Sampling was done at a depth of 0.8-1.5 meter. Prior to the sample preparation, the base soil was characterized with respect to its physical properties: specific gravity, water content, particle size analysis, and Atterberg limits. The Atterberg Limits (Liquid Limit and Plastic Limit) could not be obtained in the laboratory since the soil seemed to have been exhibiting no plasticity at all in the laboratory thus the soil is classified as non-plastic (NP). The water content ranges from 15.2 to 17%; the specific gravity is 2.662; the grain size distribution consists of gravel = 6%, sand = 92% and clay = 2%.

The Binder

The binder used in this study was an ordinary Portland cement from the Holcim Company, labelled Holcim Excel. The definition of cement content (A_w) used in this study is the ratio of dry weight of cement to the dry weight of soil and is expressed in percentage.

Reinforcing Bars

The reinforcing bars utilized in this study were 8 mm and 6 mm diameter deformed bars for main and spiral reinforcements, respectively. The definition of steel ratio (r) used in this study is the ratio of the area of longitudinal bars and the gross area of cylindrical specimens/RDMM pile.

Remolding of Base Soil

The disturbed soil samples were first thoroughly homogenized manually. Any stone and pebble, which could be found, were discarded as far as possible before mixing. The soil with the required additional water was placed inside the cement mixer and allowed to mix thoroughly for 5 minutes. The base soil used in the unconfined compression tests for unreinforced specimen was remolded with water contents ranging from the natural water content (w_o) up to $1.45w_o$. The purpose of varying the remolding water contents is to simulate the actual condition of soil-cement column/pile installation using deep mixing method with slurry of cement. Prior to the introduction of cement slurry, the natural soil was subjected to remolding and mixing with the associated addition of water, which increased the water content of the natural soil [4]. The remolding soil water content (w^*) is hereinafter defined as the water content of the remolded soil prior to the addition of cement slurry. The amount of water added to a wet soil sample in order to get the desired remolding water content was obtained using the following fundamental equation:

$$\Delta W_W = \frac{W_T}{1+\omega_o}\left(\omega^* - \omega_o\right) \tag{1}$$

where DW_W is the additional weight of water to be added in kg; W_T is the total weight of prepared original untreated soil sample in kg; w^* is the required remolding soil water content in %, and w_o is the natural water content of the sample in %.

Method of Cement-Admixed Soil Preparation

The overall mixing water content in the mixture is hereinafter called the *mixing water content* or the *total soil water content* (C_m). The total mixing water content (C_m), which is defined by Lorenzo and Bergado (2004), is represented by the equation:

$$C_m = \omega^* + (W/C)A_w \tag{2}$$

where C_m is the total mixing water content of the soil-water-cement paste (in %) reckoned from the dry weight of soil only; w^* is the remolding soil water content (in %) before mixing the cement slurry; W/C is the water-cement ratio by weight of the cement slurry; and A_w is the desired cement content (in %). In this study, the water cement ratio (W/C) used was 0.6. The remolding water contents (w^*) were w_o, $1.15w_o$, $1.30w_o$, and $1.45w_o$ and the cement contents (A_w) were 5%, 10%, 15% and 20%.

Specimen Preparation

The binder and water were mixed to make slurry. Mixing of slurry was done simultaneously with the remolding of base soil for about 5 minutes. The slurry was added to the soil and was allowed to mix for 10 minutes. The mix was filled into a cylindrical PVC moulds 150 mm in diameter and 300 mm in height, in 4-5 layers by the filling spoon. Each layer was tamped or rodded with a tamping rod to eliminate air bubbles and to knit the layers together. For easy removal of PVC molds, each mold was provided with vertical slit and tied with gauge 16 GI tie wire near the top and bottom end of the mold. The inner surface of molds was moistened with a very thin layer of oil. To prevent moisture loss, the specimens were waxed at the top faces and the bottom of the molds were filled with cement paste. On the following day, the specimens together with the molds with plastic bags were carefully transported to the place of curing and stored for 28 days in an air-conditioned cabinet with a temperature range from 22-25 °C.

III. RESULTS AND DISCUSSION

Unconfined Compression of Unreinforced Specimens

The specimen notation, for example, in the form of 115-20 means that the remolding water content (w*) is 115% of the natural water content ($1.15w_o$) and the cement content (A_w) is 20%. A plot showing the stress-strain response, peak strength and failure strain profile of unreinforced cement-admixed soil is shown in **Figure 1.** In this plot, the symbols with the same shape correspond to specimens with the same cement content and the heavier the dashed line means the higher the remolding water. As expected, the unconfined compressive strength increased with increasing cement content which is consistent with the results reported in the literature. The increase in strength with cement content is due to the reaction between cement and soil. Upon addition, cement immediately reacts with pore water and results in cation exchange and formation of cementing products that bind the soil particles together and increases the soil strength. Furthermore, it can be observed that specimens with higher cement contents have higher peak strengths and exhibited a brittle failure while specimens with lower cement contents have lower peak strengths and exhibited a ductile failure.

The Optimum Mixing Water Content

The optimum total mixing water content ($C_{m,opt}$) is hereinafter defined as the total mixing water content of the soil-water-cement paste that would give the highest possible improvement in strength of cured cement-admixed soil. As suggested by Lorenzo et al. (2006), the value of optimum mixing water content can be obtained by plotting the strength curve (**Figure 2**). This curve is a plot of

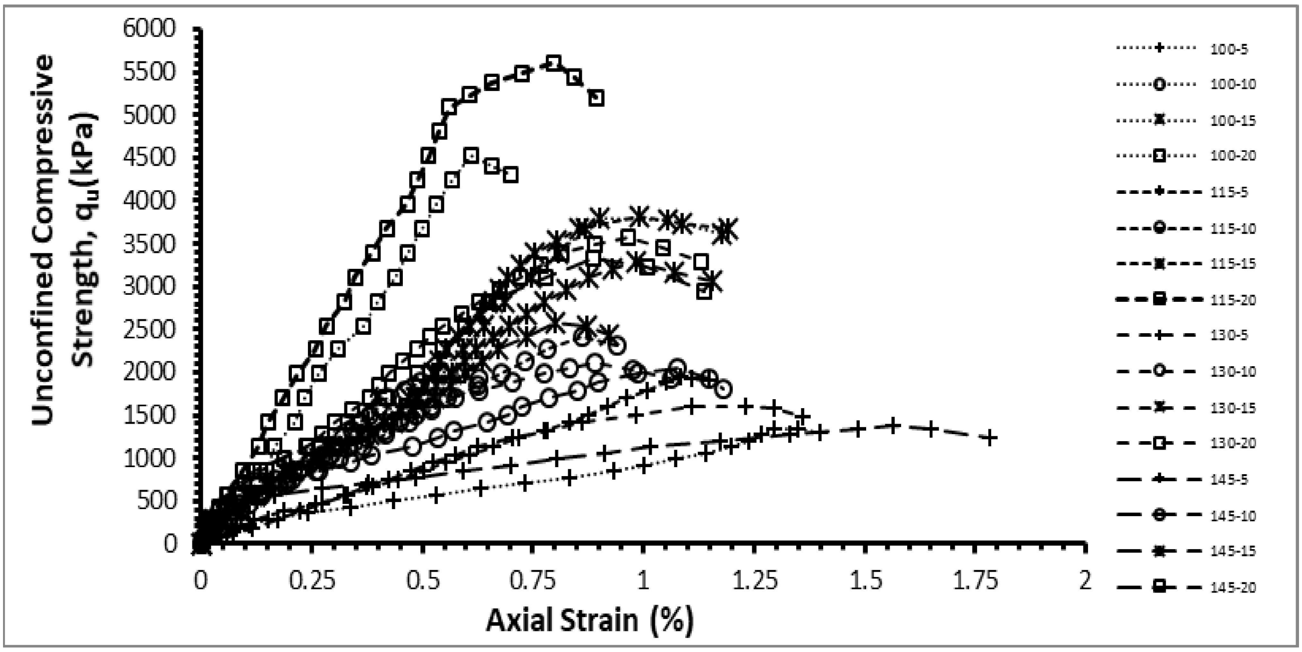


Figure 1. Stress-Strain Diagram of Unreinforced Cement-Admixed Specimens

unconfined compressive strength (q_u) versus the ratio of total mixing water content to liquid limit of the base clay (C_m/LL). This study used a non-plastic (LL=0) base soil and the mixing water content is varied from natural water content to 1.45 times the natural water content. Thus, the horizontal axis is plotted in terms of the ratio of total mixing water content to natural water content (C_m/w_o) instead of (C_w/LL). In the present study, which uses sandy soil, for a particular cement content specimens the optimum mixing water content falls at about C_m/w_o= 1.36 for A_w = 5%, 1.55 for A_w = 10%, 1.73 for A_w = 15% and 1.93 for A_w = 20%. In Figure 2, it can be noticed that the value of the ratio C_m/w_o increases as the cement content increases.

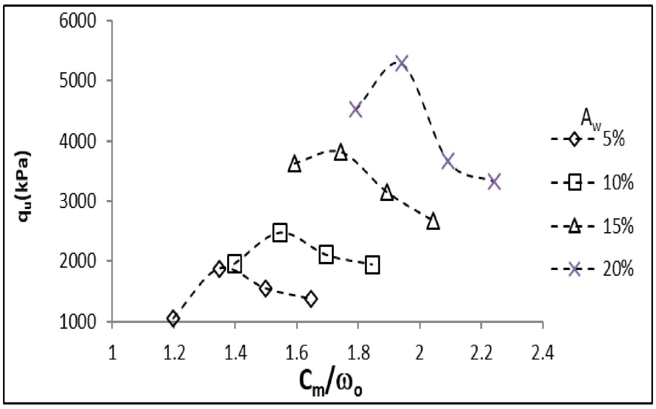


Figure 2. Strength Curve of Cement-Treated Soil

Unconfined Compression Test of Reinforced Specimen

The unconfined compressive strength tests were conducted on ninety-one (91) reinforced and nine (9) unreinforced 150 mm in diameter and 300 mm high specimens. The purpose of the tests is to study the strength and deformation behavior of cement-admixed cylindrical specimens with respect to cement content (A_w), number of longitudinal bars (n_b) and the spacing of spiral reinforcements (SS). The cement contents (A_w) used in the experiments were 10, 15 and 20%. The numbers of longitudinal bars (n_b) were 4, 6, and 8 and the spacing of spiral reinforcements were 50, 75 and 100 mm. The sizes of the reinforcing bars used in this study were 8 mm and 6 mm for longitudinal and spiral reinforcements, respectively. Testing of nine (9) unreinforced specimens was also conducted in this study in order to assess the improvement in strength of the reinforced specimens. The remolding water contents (w*) used were based on the optimum water contents (w^*_{opt}) that were obtained from the previous experiments.

A plot showing the stress-strain response, peak strength and failure strain profile of reinforced cement-admixed soil is shown in **Figure 3**. In this plot, the symbols with the same shape correspond to specimens with the same cement content; the heavier the weight of the lines means the bigger the number of longitudinal reinforcing bars and the more solid the line the closer is the spacing of spiral reinforcements. The specimen notation, for

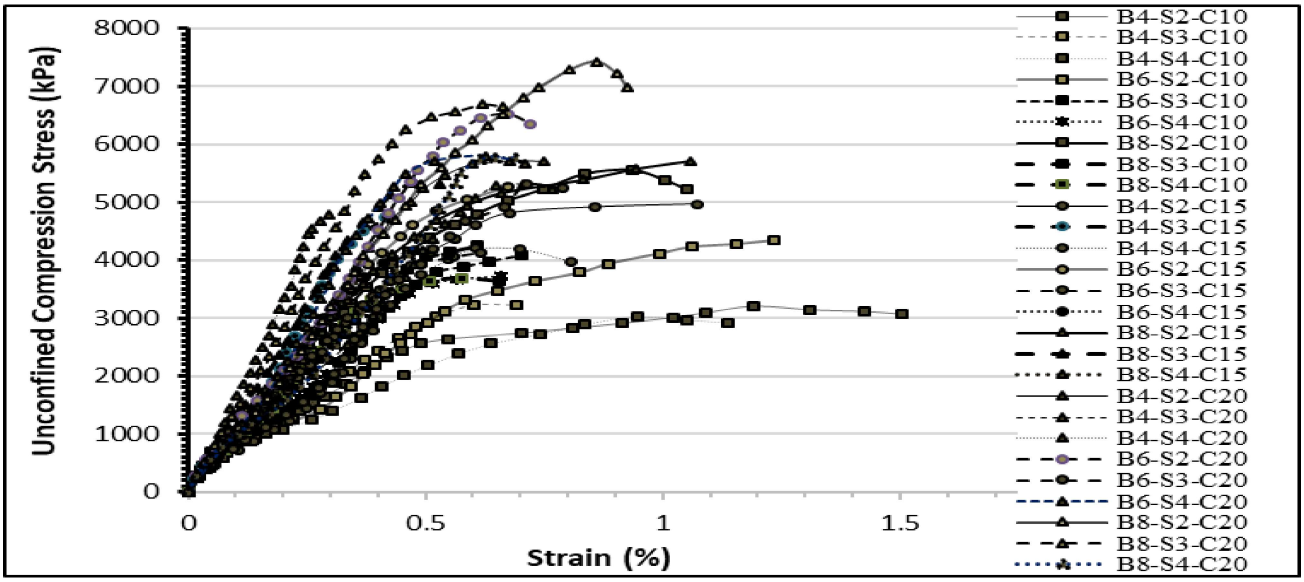
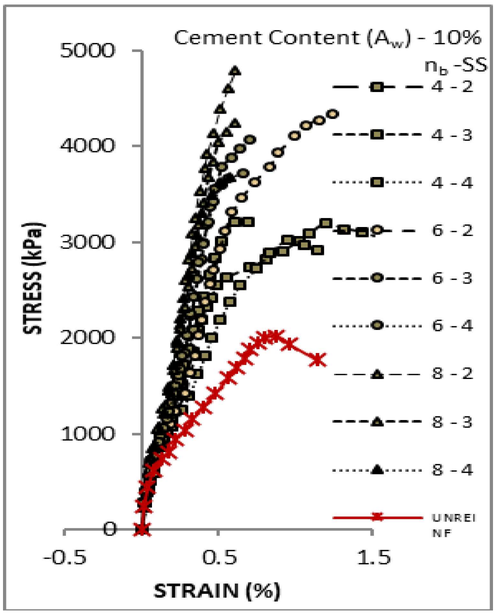


Figure 3. Stress-Strain Plot of Unconfined Compression Test on Reinforced Cement Treated Soil

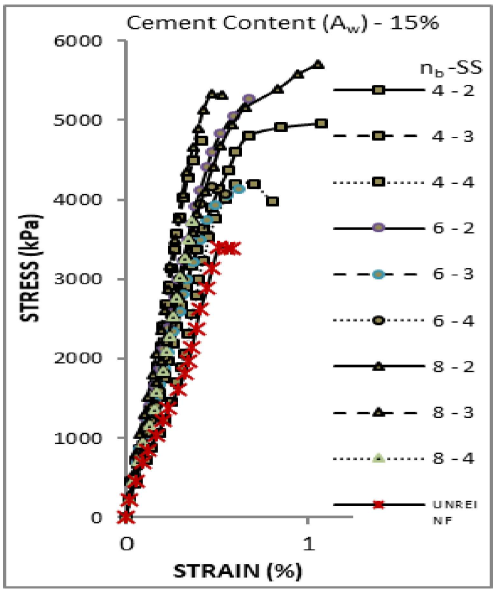
example, in the form of B4-S3-C10, means there are 4 longitudinal bars (B4); the spiral spacing is 3 inches (75mm) (S3); and the cement content is 10% (C10). The unconfined compressive strength of reinforced specimens ranges from 2883 to 7720 kPa. The lowest unconfined compressive strength (q_u) corresponds to specimen B4-S4-C10, a specimen which has the smallest number of longitudinal bars (n_b=4), the farthest spiral spacing (SS=4 inches) and has the lowest cement content (A_w=10%). The highest q_u obtained corresponds to specimen B8-S2-C20, a specimen that has the most number of longitudinal bars (n_b=8), the closest spiral spacing (SS=2 inches) and has the highest cement content (A_w =20%). In the same plot, it can be observed that the unconfined compressive strength, q_u, increased with the increasing cement content and number of main bars. Specimens with lower cement contents exhibited a brittle failure while those specimens with higher cement contents exhibited a ductile failure.

Figures 4a-c show plots of stress-strain of reinforced cement-admixed specimens grouped according to cement content (A_w). It can be noticed that at certain cement content it is evident that the specimens with the most number of main bars (n_b = 8) and closest spiral spacing (8-2) are the specimens with the highest unconfined compressive strengths. At 10% and 15% cement contents, Figure 4 (a) and Figure 4 (b), the unreinforced specimen exhibits the lowest unconfined compressive strength.

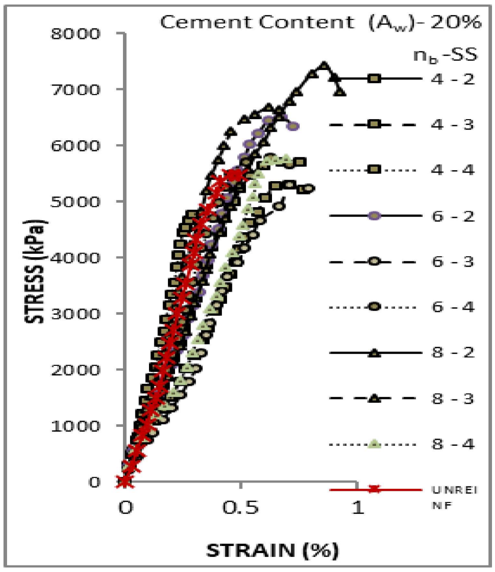
However, at 20% cement content the q_u of unreinforced specimen is higher than the specimens with smaller number of longitudinal bars and larger spiral spacing (Figure 4(c). The improvement in the q_u with respect to the increasing number of longitudinal bars (n_b) is pronounced at low cement contents. On the other hand, the contribution of the main reinforcing bars on the unconfined compressive strength of reinforced cement-admixed specimens is less significant at higher cement content.



(a) Aw = 10%



(b) Aw = 15%



(c) Aw = 20%

Figure 4. Unconfined Compression Strength Versus Axial Strain

Effects of Total Mixing Water Content

The plot of q_u versus the ratio of total mixing water content to cement content (C_m/A_w) is shown in **Figure 5**. The lines in the plot represent the trend lines for different number of longitudinal bars. Higher value of (C_m/A_w) means either the total mixing water content is high or the cement content is low. If the cement content is approaching to infinity, the value of ratio (C_m/A_w) is approaching to zero. Value of the ratio (C_m/A_w) equal to zero means that the solid particles in the soil-cement mixture purely consist of cement, thus the unconfined compressive strength of the cement-treated soil will approach to the value of unconfined compressive strength of the cement grout. On the other hand, when the value of cement content (A_w) is approaching to zero, the value of the ratio (C_m/A_w) is approaching to infinity. In this condition, the unconfined compressive strength of the cement-admixed soil will approach to the unconfined compressive strength of the native (untreated) soil. Also as shown in **Figure 5**, it can be observed that at higher value of (C_m/A_w), the strength gain with respect to the increasing number of longitudinal bars (n_b) is pronounced. Accordingly, the contribution of the main reinforcing bars on the unconfined compressive strength of reinforced cement-admixed specimens is significant at lower cement contents. On the other hand, the contribution of the main reinforcing bars on the unconfined compressive strength of reinforced cement-admixed specimens is less significant at the lower value of (C_m/A_w). The curves in Figure 5 can be normalized by introducing the following normalizing parameter:

$$\rho_v = (C_m / A_w)(1 - \rho A_w)^3 \qquad (3)$$

By doing a sensitivity analysis on the exponent of the term (1-rA_w), it turned out that 3 gives the best fit (R^2 =0.809). The plot in Figure 5 may be transformed into a normalized curve in **Figure 6** where r_v is the abscissa and q_u is the ordinate. The unconfined compressive strength, q_u, may be represented by the following function obtained from the trend line of normalized curve in Figure 6:

$$q_u = 7711 e^{-0.46(C_m / A_w)(1-\rho A_w)^3} \qquad (4)$$

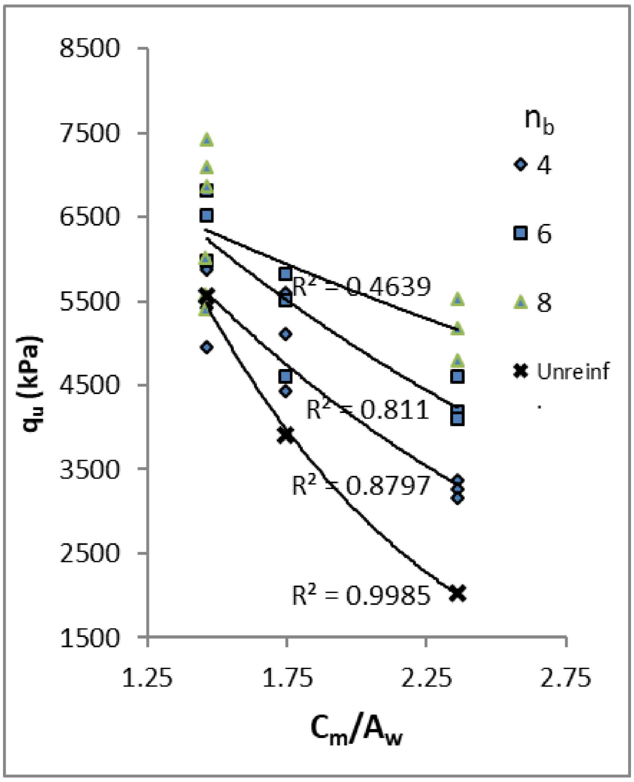


Figure 5. Unconfined Compression Strength versus C_m/A_w

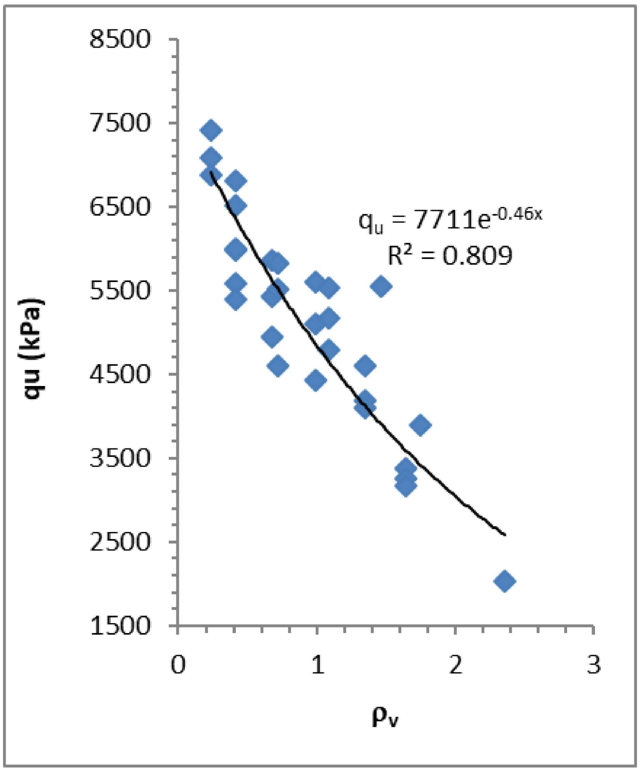


Figure 6. Normalized Unconfined Compression Strength versus ρ_v Curve

Using Equation (4), it is possible to estimate the amount of cement and the area of longitudinal bars to reach the specified unconfined compressive strength of reinforced cement admixed soil, based solely on the natural water content of the base soil. Thus, in this study an empirical model for the unconfined compressive strength of reinforced deep mixing pile is proposed.

Full Scale Simulation on the Compression Behavior of Single RDMM Pile

A full-scale RDMM pile was installed and subjected to static load test to measure its vertical displacement and bearing capacity. Because of the difficulty and high cost of full-scale test, only one (1) RDMM pile was considered in this study. Axial load test was conducted in accordance with ASTM D-1143, *Quick Load Test Method for Individual Piles Under Static Axial Compression Load*. **Figure 7** and **Figure 8** show the schematic diagram and the actual set-up of pile load test, respectively. The

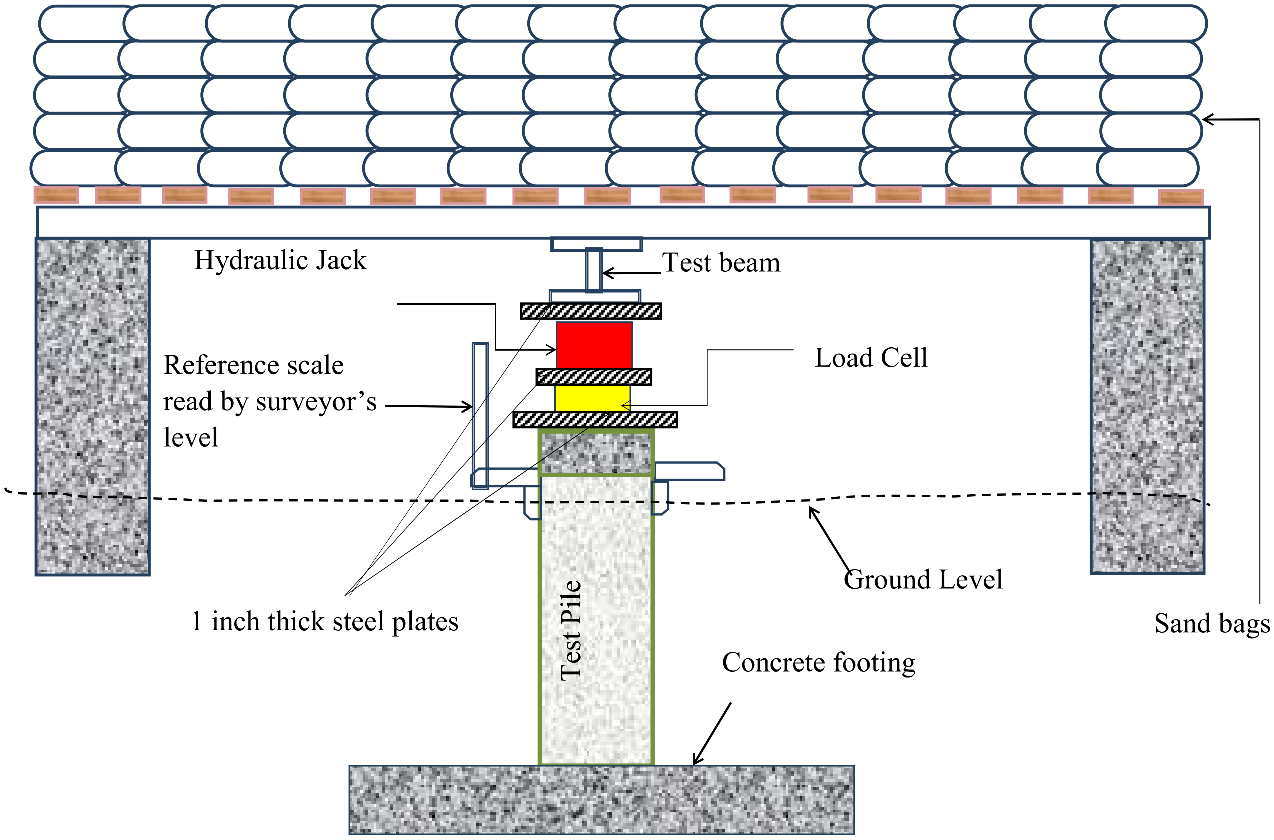


Figure 7. Schematic Diagram of Pile Load Test

Figure 8. Pile Load Test Set Up

RDMM pile is 300 mm in diameter and 2 m in height and spirally reinforced with 88 mm diameter longitudinal bars and 6 mm diameter spiral bars spaced at 75 mm. To ensure a pile failure, a concrete footing of approximately1.5 m in diameter and 300 mm thick was constructed below the RDMM pile. The empirical model, given by Equation 4, was used to estimate the capacity of reinforced deep mixing pile. Based on the given parameters and using Equation 4, the estimated peak stress of reinforced deep mixing pile is 3930 kPa or equivalent to 278 kN axial load.

The behavior of reinforced deep mixing pile subjected to monotonic loading is shown in **Figure 9.** It can be seen that the maximum load of 180 kN was reached at 51 mm displacement. Hence, the failure load of full-scale RDMM pile of 180 kN is only 60% the estimated ultimate capacity based on the proposed empirical equation. The actual failure load, therefore, is close to the lower limit of the empirical model, which could be attributed to the consequent different boundary conditions and rate of loading between laboratory test and the field test. According to Cement Deep Mixing Association of Japan CDM (1994), the unconfined compressive strength of cement-treated soil collected from the field is usually only one-half to one-fifth (1/2 – 1/5) of the strength of laboratory-prepared specimens. The possible reasons for such discrepancies are attributed to the problems associated with the different boundary conditions and rate of loading between laboratory tests and the field test.

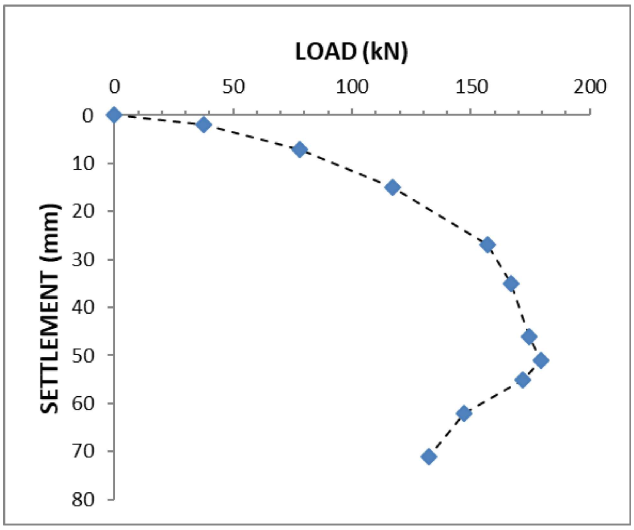


Figure 9. Load-Settlement Curve of Single RDMM Pile

IV. CONCLUSIONS

This study has investigated through laboratory and field simulations the strength and deformation behavior of a cement-admixed non-plastic soil reinforced with deformed steel bars for deep mixing ground improvement application. The following conclusions are drawn from this study:

1. The unconfined compressive strength of cement-admixed soil increased with increasing cement content and it decreases with increasing total mixing water content.
2. The cement-admixed soils with high cement content have higher peak strengths and exhibited brittle failures, while the specimens with low cement content have lower peak strengths and exhibited ductile failures.
3. Cement content (A_w), number of longitudinal bars (n_b) and spacing of spiral reinforcement) SS have significant contributions to the strength gain of reinforced cement-admixed soil.
4. The UCS is increased with the increasing cement content and increasing steel ratio (r).
5. The improvement in the UCS with respect to the increasing number of longitudinal bars ($n_{b)}$ is pronounced at low cement contents. On the other hand, the contribution of the main reinforcing bars on the unconfined compressive strength of reinforced cement-admixed specimens is less significant at higher cement content.
6. Empirical equation that predicts the unconfined compressive strength of reinforced cement-admixed non-plastic soil is proposed.
7. The failure load of full-scale RDMM is 180 kN, which is only 60% the estimated ultimate capacity based on the proposed empirical equation. The lower failure load could be attributed to the problems associated with the different boundary conditions and rate of loading between laboratory test and the field test.

REFERENCES

[1] Kamon, M., and Bergado, D.T. (1991). Ground Improvement Techniques. *Proceedings, 9th Asian Regional Conference on Soil Mechanics and Foundation Engineering*. Vol. 2, Bangkok, Thailand, 526-646.

[2] Porbaha, A. (1998). "State of the Art in Deep Mixing Technology. Part I: Basic Concepts and Overview". Ground Improvement. 2, 81-92.

[3] Asturias, R.P. and Lorenzo, G.A. (2015) Laboratory and Full-Scale Simulations of the Behaviour of Reinforced Cement-Admixed Non-Plastic Soil for Deep Mixing Applications, International Journal of Scientific Engineering and Technology. Vol. 4 Issue No. 5, 286-289.

[4] Lorenzo, G.A. and Bergado, D.T. (2006). Fundamental Characteristics of Cement-Admixed Clay in Deep Mixing. Journal of Materials in Civil Engineering, ASCE, 161-174.

[5] Lorenzo, G.A. and Bergado, D.T. (2004). Fundamental Characteristics of Cement-Admixed Clay-New Approach. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 130(10), 1042-1050

[6] Lorenzo, G. A., Bergado, D. T. and Soralump, S. (2006). —New and Economical Mixing Method of Cement Admixed Clay for DMM Application.� Geotechnical Testing Journal, ASTM, 29 (11), 54-63.

[7] ASTM D1143-94 (1994). Standard Test Method for Pile Under Static Axial Compression Load, Annual Book of ASTM Standards.

[8] Asturias, R.P. (2014). Laboratory and Full-Scale Simulations of the Behavior of Reinforced Cement-Admixed Iligan City Alluvial Soil for Deep Mixing Applications. Doctor of Engineering Dissertation, MSU-Iligan Institute of Technology, Iligan City, Philippines. CDM (1994). Publication of Cement Deep Mixing Association of Japan, Tokyo, pp. 1-194. (in Japanese)