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Laboratory and Full-Scale Simulations of the Behaviour of Reinforced Cement-Admixed Non-Plastic Soil for Deep Mixing Applications

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Abstract*: This paper proposes a new soil treatment method that employs reinforced deep mixing method (RDMM). In this method, the deep mixing pile is reinforced in a manner similar to a spirally reinforced concrete column. This paper aimed to evaluate the effectiveness of RDMM on improving the strength and deformation properties of a non-plastic soil. Four (4) experimental phases are conducted in this study and these are: 1) Physical property tests of the base soil, (2) Unconfined compressive strength (UCS) tests on unreinforced cement-admixed soil specimens, (3) Unconfined compressive strength tests on reinforced cement-admixed soil specimens, and (4) Construction and load testing of full-scale reinforced deep mixing pile. The results unconfined compressive strength tests revealed that the influence of longitudinal bars on the unconfined compressive strength of reinforced cement-admixed non-plastic soil is pronounced at low cement contents.

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

I. Introduction

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 column shaped, 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 (Kamon and Bergado 1991; Porbaha 1998).

In this paper, a new soil treatment method that employs reinforced deep mixing method (RDMM) is proposed. In this method, the deep mixing pile is reinforced in a manner similar to reinforced concrete columns or piles. The addition of reinforcing bars is expected to increase the stiffness and bearing capacity of soil-cement pile. Furthermore, the lateral confinement created 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. RDMM can be used as pile foundation for lightly loaded structures as an alternative to expensive reinforced concrete piles. RDMM has several advantages over the existing concrete piles in terms of construction and economy because it uses the in-situ 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 on 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 bigger portion of the load is carried by the shaft resistance. The strength of these piles is utilized in the handling and driving operation during the construction stage.

II. Material and Methodology

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, labeled Holcim Excel. The definition of cement content (Aw) 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 (ρ) 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

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remolded with water contents ranging from the natural water content (ω_o) up to 1.45ω_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 (Lorenzo and Bergado, 2006). The remolding soil water content (ω*) 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:

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

where ΔW_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; ω* is the required remolding soil water content in %, and ω_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:

$$C_m = \omega^* + \left(W/C\right)A_w \qquad (2)$$

where C_m is the total mixing water content of the soil-water-cement paste (in %) reckoned from the dry weight of soil only; ω* 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 Aw is the desired cement content (in %). In this study, the water cement ratio (W/C) used was 0.6. The remolding water contents (ω*) were ω_o, 1.15ω_o, 1.30ω_o, and 1.45ω_o and the cement contents (Aw) 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 ends 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 and were carefully transported to the place of curing and stored for 28 days in an air-conditioned curing cabinet with a temperature ranges from 22-25^{o}C.

III. Results and Discussions

Unconfined Compressive Test (Reinforced)

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 (Aw), number of longitudinal bars (n_b) and the spacing of spiral reinforcements (SS). The cement contents (Aw) used in the experiments were 10, 15 and 20%. The numbers of longitudinal bars (n_b) were 4, 6, and 8 and the spacings of spiral reinforcements were 50, 75 and 100 mm. 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 (ω*) used were based on the optimum water contents (ω^*_{opt}) that were obtained from the previous experiments.

A plot of showing the stress-strain response, peak strength and failure strain profile of reinforced cement-admixed soil is shown in Fig 1. 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 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 (Aw=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 (Aw =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. Furthermore, it can be noticed that specimens with lower cement contents exhibited a brittle failure while those specimens with higher cement contents exhibited a ductile failure.

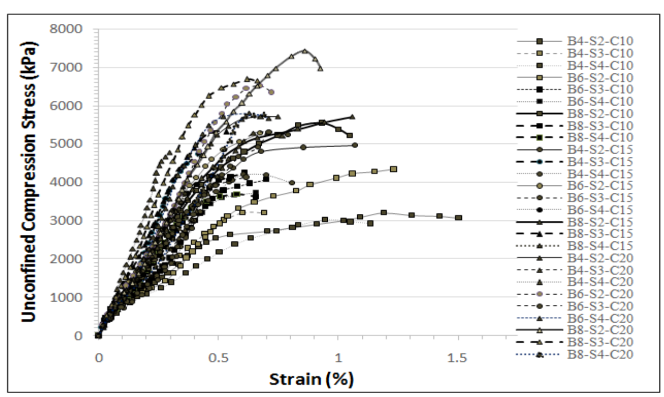

Fig.1 . Stress-Strain Plot of Unconfined Compressive Test on Reinforced Cement Treated Soil.

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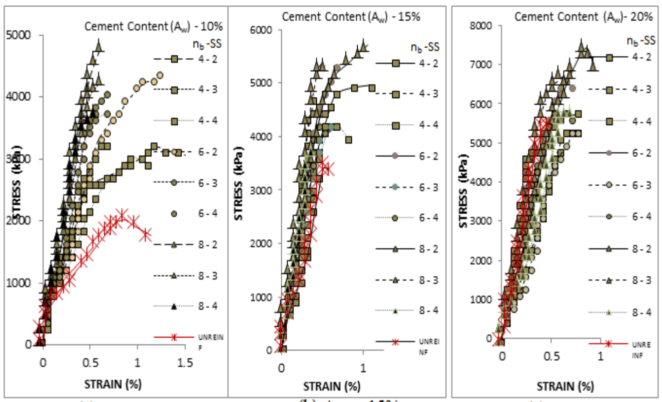
Fig 2a-c show plots of stress-strain of reinforced cement-admixed specimens grouped according cement content (Aw). It can be noticed that at certain cement content it is evident that the specimens with the most number of main bars ($n_b = 8$) and closest spiral spacing (SS = 2) are the specimens with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

Fig 2. Unconfined Compressive Strength Versus Axial Strain

However, at 20% cement content the unconfined compressive strength of unreinforced specimen is higher than the specimens with smaller number of longitudinal bars and larger spiral spacing (Fig 2c). The improvement in the unconfined compressive



(a) Aw = 10% (b) Aw = 15% (c) Aw = 20%

strength 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.

Effects of Total Water Mixing Content

The plot of q_u versus the ratio of total mixing water content to cement content (C_m/Aw) is shown in Fig 3. The lines in the plot represent the trend lines for different number of longitudinal bars. Higher value of (C_m/Aw) 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/Aw) is approaching to zero. Value of the ratio (C_m/Aw) equal to zero means that the solid particles in the soil-cement mixture is 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 (Aw) is approaching to zero, the value of the ratio (C_m/Aw) 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 Fig 3, it can be observed that at higher value of (C_m/Aw) 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/Aw). The curves in Fig 3 can be normalized by introducing the following normalizing parameter:

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

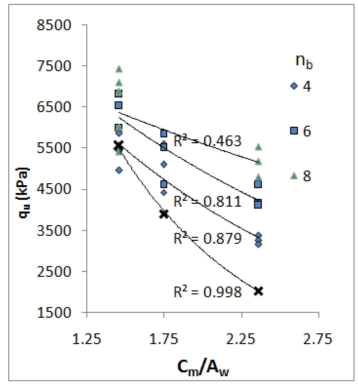


Fig .3 Unconfined Compressive Strength Versus C_m/A_w Curve.

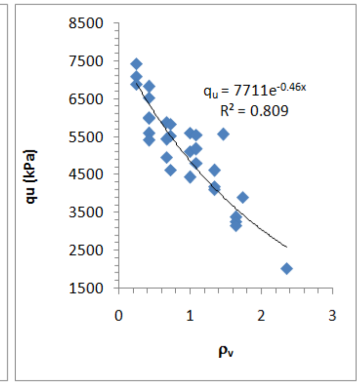


Fig 4. Normalized Unconfined Compressive Strength Versus ρ_V Curve.

By doing a sensitivity analysis on the exponent of the term (1-ρA_w), it turned out that 3 gives the best fit (R^2 =0.809). The plot in Fig 3 may be transformed into a normalized curve in Fig 4 where ρ_v as the abscissa and q_u as the ordinate. The unconfined compressive strength, q_u, may be represented by the following function obtained from the trend line of normalized curve in Fig 4:

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

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.

IV. Conclusions

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 (Aw), 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(ρ).

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.

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