Unconfined Compression Behavior of Cement Treated Non-Plastic Soil Reinforced with Small Diameter Steel Bars

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Abstract-- Series of unconfined compression tests were performed to evaluate the strength and deformation behavior of cement-treated non-plastic soil with small diameter spiral steel reinforcement. The tests included 48 unreinforced and 81 reinforced cylindrical specimens, 150 mm diameter and 300 mm high. The parameters investigated in the unreinforced specimens were the remolding water contents, cement contents and after-curing parameters. Results of unconfined compression tests on unreinforced specimens revealed that the ratio of optimum total mixing water content to the natural water content ($C_{w/o}$) increases with the increasing cement content. The parameters investigated in the reinforced specimens were the pitch of the spiral reinforcement, number of longitudinal reinforcements and cement contents. Results of this study indicated that the use of steel reinforcement could lead to an increased load carrying capacity and a more ductile behaviour.

Index Term -- Deep mixing method, unconfined compression, cement-admixed soil, non-plastic soil

I INTRODUCTION

Ground improvement by deep mixing method (DMM) is an effective and economical method in improving the engineering properties of problematic soil. DMM can effectively increase the soil bearing capacity, reduce compressibility and permeability and increase resistance against liquefaction. This technology was started in Japan in the late 1970’s and spread in other parts of the world. In conventional DMM, the chemical agents, which are either powder or slurry, are injected and mixed thoroughly into the soil at a specific depth to improve the in-situ soil properties. The stabilized soil, often called deep mixing pile or deep mixing column, 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], [3].

The ground improved by DMM has relatively low strength and stiffness compared to conventional pile foundation. Hence, low bearing capacity and large settlement would still be a problem if DMM is used as foundation for medium rise building and other similar structures. Besides, DMM is also relatively weak in tension. As an attempt to solve the said problem of low strength and stiffness, this study investigated the effects of reinforcing the DMM pile with small diameter deformed steel bars. In this proposed method, the deep mixing pile is reinforced in a manner similar to reinforced concrete piles. The addition of reinforcing bars can effectively increase the strength and stiffness of cement-treated soil. Furthermore, the lateral confinement created by the spiral reinforcement is expected to increase the strength and control the deformation of deep mixing pile.

II METHODOLOGY

Laboratory Test on Cement-Admixed Soil

The soil used in this study was taken inside the campus of Mindanao State University-Iligan Institute of Technology (MSU-IIT), Tibanga, Iligan City Philippines. Samples were extracted from 0.8 to 1.5 m depth. The soil properties are summarized in Table I and the particle size distribution is shown in Fig. 1. The soil is classified as non-plastic (NP) with natural water content ($\omega_o$) ranges from 15.2 to 17% and the specific gravity is 2.662. Ordinary Portland cement from the Holcin Company was used as the main additive to soil. 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. The reinforcing bars utilized in this study are 8 mm and 6 mm diameter deformed bars for main and spiral reinforcements, respectively. The definition of steel ratio (p) used in this study is the ratio of the area of longitudinal bars and the gross area of cylindrical specimens.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Characteristic value</th>
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<tbody>
<tr>
<td>$D_{10}$</td>
<td>0.172</td>
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<tr>
<td>$D_{30}$</td>
<td>0.32</td>
</tr>
<tr>
<td>$D_{60}$</td>
<td>0.495</td>
</tr>
<tr>
<td>Coefficient of Uniformity, Cu</td>
<td>2.878</td>
</tr>
<tr>
<td>Coefficient of Curvature, Cc</td>
<td>1.203</td>
</tr>
<tr>
<td>Gravel</td>
<td>6%</td>
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<tr>
<td>Sand</td>
<td>92%</td>
</tr>
<tr>
<td>Clay and Silt</td>
<td>2%</td>
</tr>
</tbody>
</table>

Table I

Particle-Size Distribution and Classification of Soil
Sample Preparation

The mass of soil sample was used as a base for the calculation of the required amount of cement and water. The base soil used in the unconfined compression tests for unreinforced specimens was remolded prior to the introduction of cement slurry. The total mixing water content \( C_m \) in the mixture was determined by using the equation defined by [4], and is represented by:

\[
C_m = \omega^* + (W/C)A_w
\]

where \( C_m \) is the total mixing water content of the soil-water-cement paste (in %) reckoned from the dry weight of soil only; \( \omega^* \) 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 %). The cement contents \( (A_w) \) used in this study were 5, 10, 15 and 20% for unreinforced specimens. The remolding water contents used in the unreinforced specimens are in terms of the natural water content \( (\omega_n) \): \( \omega_n, 1.15\omega_n, 1.3\omega_n, \) and \( 1.45\omega_n \). Since the value of the natural water content \( (\omega_n) \) during the conduct of this experiment was 15.2%, thus, the equivalent remolding water contents are 15.2%, 17.48%, 19.76% and 22.04%.

The soil samples with required remolding water were mixed in a rotary mixer for five (5) minutes. The cement slurry, having water-cement ratio (\( W/C \)) of 0.6, was then added into the remolded soil samples and were allowed to mix for 10 minutes. The soil-cement-water paste was filled into a cylindrical PVC moulds 150 mm diameter and 300 mm high, 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 stored for 28 days in an air-conditioned curing box with a temperature ranges from 22-25°C (Fig 2).

For reinforced cement-admixed soil, all specimens were prepared at an optimum remolding water content \( (\omega^*_{opt}) \) obtained from the results of unconfined compression tests on unreinforced specimens. All specimens were casted in a PVC mold of 150 mm diameter and 300 mm high. Prior to the pouring of soil-cement paste, the steel encasement is inserted inside the PVC mold. During the filling of soil-cement paste into the PVC mold, the steel encasement is pushed down firmly to prevent it from moving horizontally. The vertical alignment of steel encasement is monitored during the entire process of filling of paste into the PVC mold. The mold is filled with soil-cement paste into 4-5 equal layers and each layer is compacted to remove the presence of entrapped air bubbles. The molds together with the specimens are waxed to prevent moisture loss. The methods of storing, curing and testing, and data recording and processing of specimens are the same with unreinforced specimens.

Mixing in the laboratory was done using a mini-one bagger cement mixer. The mixer has a maximum mixing capacity of 140 liters. The drum RPM is fixed at 20. The engine motor is 1/3 hp and electrically operated at 115 Volts.

Physical Property Test

Soil property tests were performed both on the base soil and the treated soil. Tests included moisture contents, specific gravity, particle size analysis, Atterberg limits and soil classification. Physical property tests investigate the basic changes of the physical properties of soil due to the addition of cement admixtures. The knowledge on the physical properties of stabilized soil is crucial to have a deeper understanding on the behavior of cement-admixed soil as geomaterial. The formation of new compounds in the soil due to hydration process of cement and the subsequent pozzolanic reaction can be qualified from the consequent changes of physical properties of the stabilized soil [5].

Unconfined Compression Tests on Unreinforced Cement-Admixed Specimens

Unconfined compression strength tests were carried out on forty-eight (48) cylindrical specimens. These tests were conducted to study the strength and deformation behavior of unreinforced cement-admixed cylindrical specimens with respect to remolding water contents and cement contents.
Furthermore, this experiment was also conducted to determine the optimum mixing water content, which is an important parameter in the sample preparation for reinforced cement admixed specimens.

Unconfined Compression Tests on Reinforced Cement-Admixed Specimens

The focus of the tests is to study the strength and deformation behavior of cement-admixed soil specimens reinforced with small diameter deformed steel bars. Unconfined compression tests on eighty-one (81) cylindrical specimens were conducted, in accordance with ASTM C39, in order to determine the effects of steel reinforcements as well as cement content \(A_w\) on the strength and deformation behavior of reinforced cement-admixed soil. These tests assess the strength test that assesses the strength improvement characteristics of deep mixing piles under various conditions of steel reinforcement and cement content. The test parameters include the number of longitudinal reinforcements \(n_b\) of 4, 6 and 8 pcs.; spacing or pitch \(SS\) of spiral reinforcement of 50, 75 and 100 mm and cement contents \(A_w\) of 10%, 15% and 20%. All specimens have 20 mm clear covering. Fig. 3 shows a schematic diagram of reinforced cement-admixed specimen.

III RESULTS AND DISCUSSIONS
Physical Property Test of Unreinforced Cement-Admixed Soil Specimens

Figure 4 shows the plot of after-curing unit weight \(\gamma_{oc}\) versus cement content \(A_w\) at different remolding water contents \(\omega^*\) of unreinforced cement-admixed soil specimens. The after-curing unit weight is equal to the weight divided by the volume of cured specimen. As shown in the same figure, the after-curing unit weight increased with the increasing cement content. The increase in unit weight with the increased cement content is due to the increasing amount of cementing products being formed, which eventually increased the weight of soil solids per unit volume. Furthermore, as depicted in the same figure, the unit weight of the cured cement-admixed soil decreased with increasing remolding water content. The decrease in unit weight with the increase in remolding water content is attributed to the subsequent increase of volume of soil voids per unit volume of treated soil. The result of this experiment is consistent with the results reported in the literature i.e.\[4\].

Unconfined Compression Tests on Unreinforced Cement-Admixed Soils

A plot showing the stress-strain response, peak strength and failure strain profile is shown in Fig 6. In this plot, the symbols with the same shape correspond to specimens with the same cement content and line types correspond to remolding water content. The plot of after-curing water content \(\omega_{oc}\), which is the ratio of the weight water to the weight of solid after curing, versus cement content at different remolding water contents is shown in Fig. 5. It can be observed that the after-curing water content decreases slightly with increasing cement content. The reason why the after-curing water content decreased with increasing cement content is due to the consumption of water and the formation of new soil solids in cement hydration process. A small amount of water will also evaporate as a result of increased heat of hydration. It can also be observed that the higher the remolding water content, the higher the after-curing water content also of the cured cement-cement admixed soil.
contents. As shown in the same figure, the unconfined compressive strength increased with increasing cement content. The increase in strength with cement content is due to the reaction between cement and soil. Cement reacts with pore water and results in cation exchange and formation of cementing products that bind the soil particles together and thereby increases the soil strength. The highest value of UCS is 5,608 kPa which corresponds to specimen 17.48-20, a specimen with remolding water of 17.47% and cement content of 20%. The lowest UCS value is 1,344 kPa which corresponds to specimen 15.2%-5.

**Effects of Remolding Water Contents**

Figure 7 shows the plot of unconfined compressive strength versus cement content. At certain cement content, it shows the comparison of unconfined compressive strengths at different remolding water contents (ω*). It can be observed that at certain cement content, the cement-admixed soil remolded at 17.48% yielded the highest UCS. Also, for specimens remolded at natural water content (15.2%), the strength improvement is pronounced as cement contents increases. However, for specimens remolded at higher water contents (i.e. 19.76% and 22.04%), the strength improvement is less pronounced as compared to the specimens remolded at lower water contents. Furthermore, specimens remolded at 22.04% have the lowest UCS as the cement content increases. The decrease in UCS with the increase in remolding water content is attributed to bigger amount of water content making the material softer and less stiff, thus developing weak bonding between the cement and the soil particles.

**Stiffness**

The modulus of elasticity of cement-admixed soil has been investigated from the unconfined compressive tests. The secant modulus at 50% failure stresses ($E_{50}$) are estimated from the stress-strain responses of the cement-admixed soils. The parameter $E_{50}$ is measured as the slope of stress-strain curve at 50% of the failure stress. As shown in Fig 8, the secant modulus ($E_{50}$) of cement-admixed soil ranges from 122,000 kPa to 873,000 kPa with UCS of 1,300 kPa to 5,600 kPa, respectively. Moreover, the ratio $E_{50}/q_u$ is between 91 to 167. Thus, in this study the correlation of secant modulus of 132.2$q_u$ is obtained, which is in agreement with those reported in the literature, [6], [7] & [8].

**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 [9], the value of optimum mixing water content can be obtained by plotting the strength curve (Fig 9). This curve is a plot of...
unconfined compressive strength \( (q_u) \) versus the ratio of total mixing water content to liquid limit of the base clay \( (C_m/\omega_0) \). This study used a non-plastic base soil and the mixing water contents ranging 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 \( (C_m/\omega_0) \) instead of \( (C_m/\omega_c) \).

In the study of [9] which utilized soft Bangkok clay, the optimum mixing clay water content falls within the range of 1 to 1.1 times the liquid limit of the base clay. In the present study, which used sandy soil, for a particular cement content the optimum mixing water content falls at about \( C_m/\omega_0 = 1.36 \) for \( \omega_c = 5\% \), 1.55 for \( \omega_c = 10\% \), 1.73 for \( \omega_c = 15\% \) and 1.93 for \( \omega_c = 20\% \), as shown in Figure 4. Also in the same figure, it can be seen that the value of the ratio \( C_m/\omega_0 \) increases as the cement content increases.

\[
q_u = A\rho e^{B(\omega_c/\omega_0)}
\]

Effect of After-curing Void Ratio, \( e_{\omega}/A_{\omega} \)

The effects of the ratio of after-curing void ratio to cement content, \( e_{\omega}/A_{\omega} \), on the unconfined compressive strength are investigated. The after-curing void ratio, \( e_{\omega} \), adapted by [4] takes into account the effect of total mixing water content, cement content, curing time as well as curing pressure on the UCS of cement-admixed clay. The plot of unconfined compressive strength versus the ratio of after-curing void ratio to cement content is shown in Fig 10. From the following empirical relationship derived by [4],

\[
q_u = A\rho e^{B(\omega_c/\omega_0)}
\]

this study has obtained the values of dimensionless constants \( A=49.65 \) and \( B=0.12 \). These values are much higher as compared to the value obtained by [4]. In the study of [4] which utilized soft Bangkok clay mixed with Type I Portland cement, the value of dimensionless constants are: \( A=10.33 \) and \( B=0.046 \). Constant \( A \) is dependent and affected by the type of admixture, while constant \( B \), is basically the slope of the mean function in Fig 10, is dependent and affected by the type and mineralogy of the base clay [4]. Higher values mean higher strength improvement on the cement-admixed soil. This is expected since the present study used sandy base soil and the previous study utilized clayey soil. In soil stabilization, for given cement content, coarse grained soil has a larger strength increase as compared to fine grained soil.

Unconfined Compression Tests on Reinforced Cement-Admixed Soils

The plot showing the stress-strain responses is shown in Fig 11. In this plot, the symbols with the same shape correspond to specimens with the same cement content, the darker the fill of the shape means the bigger the number of longitudinal reinforcing bars and the more solid is 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 (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 (\( n_l=4 \), the farthest spiral spacing (SS=4 inches) and has the lowest cement content \( (A_{\omega}=10\%) \). The highest \( q_u \) obtained corresponds to specimen B8-S2-C20, a specimen that has the most number of longitudinal bars (\( n_l=8 \), the closest spiral spacing (SS=2 inches) and has the highest cement content \( (A_{\omega}=20\%) \). 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 ductile failure while those specimens with higher cement contents exhibited a brittle failure.
IV CONCLUSIONS

A. Unreinforced specimens:

The unconfined compressive strength increased with increasing cement content. The unconfined compressive strength of cement-admixed soil decreases with increasing total mixing water content. The cement-admixed soils with high cement content have higher peak strengths and exhibited brittle failure while the specimens with low cement content have lower peak strengths and exhibit ductile failure. As the cement content increases, the strength gain of specimens remolded at low water contents is more pronounced as compared to the specimens remolded at high water contents. For non-plastic soil, the optimum total mixing water content is a function of cement content (A_w). It was observed that at optimum strength the ratio of total mixing water content to natural water content (C_w/οw) increases with increasing cement content.

B. Reinforced Specimens.

The highest value of unconfined compressive strength obtained from the test corresponds to a specimen that has the most number of longitudinal bars, the closest spiral spacing and has the highest cement content. On the other hand, the lowest UCS value corresponds to the specimen that has the least number of longitudinal bars, the biggest spiral spacing and has the lowest cement content. This proves that each parameter (A_w, n_o, SS) considered in this experiment has a significant contribution to the strength gain of reinforced cement-admixed soil. The UCS increases with increasing cement content. Specimens with lower cement contents exhibited low peak strength and exhibited a ductile failure while those specimens with higher cement contents exhibited higher peak strength and brittle failure. The UCS increases with increasing steel ratio (p). Specimens with lower steel ratio (p) exhibited low peak strength and ductile failure while those specimens with higher steel ratio (p) exhibited higher peak strength and brittle failure. At certain cement content, the strength and ductility increased with decreasing spiral spacing. This is attributed to the confining effects of spiral reinforcements.

This research has shown that the addition of steel reinforcement improved the unconfined compression strength and stiffness of conventional DMM pile. With the improved strength, reinforced DMM can be used as an alternative to a very expensive pile foundation for light to medium loaded structures. Furthermore, the results of experiment can be used to develop a mathematical model that can estimate the unconfined compression strength of reinforced DMM pile. The mathematical model can be verified by conducting a load test on full scale reinforced DMM.

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