Mechanical behavior of Vinh Long soil mixed with cement

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Abstract. Recently, deep soil mixing has been constructed in Vietnam. However, the researchers applying this solution to reinforce soft ground with geological conditions of Vinh Long are not common. This paper concentrates on study of mechanics of soil samples which are compatible with Vinh Long geological conditions. Experiments on unconfined compressive strength were performed to analyze mechanical behaviors in the duration of curing samples. Soils taken from two layer of researching area were mixed with cement with the content from 150 kg/m³ to 250 kg/m³, then were curing in duration of 7 days, 14 days, 28 days and 60 days. Results of tests at specified timeline show that unconfined compressive strength of most mixing samples increases with the cement content and curing period. The secant modulus of elasticity is determined from the deformation resistance test, then the loading capacity of samples can be deduced. The secant modulus of elasticity increases when the unconfined compressive strength increases. This article is a valuable reference in the design of cement-reinforced soft soil for application in infrastructure engineering.

1. Introduction
Deep soil mixing solution has been applied widely in many fields such as: transportation, bridge, irrigation, urban infrastructure and especially in reinforcing soft soil. The feasibility of this solution depends on loads, construction capability as well as the site geological characteristics. Transportation has been convenient and the economic has been develop strongly after My Thuan bridge was built. Therefore the province infrastructure has been invested. Because Vinh Long geology is rather soft, around 20 m of soil on the top is clay mud, it is quite complicated to improve soft soil in order to limit the settlement and construction progress. Cement piles are recommended with advantages such as wide range of application, suitable with all kinds of soil are recommended, local treatment without affecting stronger layer, construction in submerged conditions, small construction site plan, less vibration and noise, fast execution, uncomplicated construction techniques, low risk factor and less environmental pollution. There is not much publication on study of cement pile strength in Vinh Long province thus it is necessary to do this research.

The objective of this paper is to determine the unconfined compressive strength (q_u) in the curing duration and the behavior of 2 types of Vinh Long mixing soil with different cement content. This article clarifies the mechanical behavior of soil mixing, provides data to generalize the applicability of mixing in improving soil for area with similar geology. This paper is a useful reference for design
engineers and investors in choosing the soft soil treatment method in Vinh Long province in order to achieve high efficiency in techniques and economics.

2. Literature review
Deep soil mixing has been studied and applied in practice for the past four decades, starting from Sweden and Japan and now is popular technical method in foundation reinforcement [1-3]. Two common methods of construction are dry jet mixing and wet jet mixing. Dry mixing is the method in which dry binders are blown into the ground by compressed air while jet – grouting is technique that binders – water is blown into the ground by compressed air. In general, soil-cement pile can be applied in many types of constructions such as embankment, deep excavation supporting or foundation for tall building [4-5].

In the last few decades, many researches on soil mixing were published. These publications followed two common approaches, which are: The first method is based on the physical properties of material. Donal A. Bruce (2000) [1], Ajarloo A.M (2010) [4] presented the results of research on different types of soil in France and in the USA. Jacobson et al. (2003) [5] studied the efficiency of lime cement pile to enhance dam stability. Kitazume et al. (2013) [6] found out accurate results regarding to strength of soil cement pile. In the same curing time, with various content of cement, the strength of mixing are different, the higher the cement content, the greater the strength of mixing [3] [11] [12]. The second method is develop to consider the effectiveness of mixing in the application of tall building foundation, that take into account the mechanical properties of single pile and pile group like Broms (1999) [7], Japan (2001) [8], Jie Han (2004) [9], Bouassida (2009) [10].

Testing on many kinds of sand, most of them are easily achieved an intensity of 5 MPa to 10 MPa in terms of unconfined compressive strength. Thus, deep soil mixing can be used for foundations of tall buildings as load bearing piles. In practice, many successful cases both in Vietnam and abroad are recently reported in specialized materials [13-21].

3. Materials and Methods
Research was done through laboratory experiments. The method of sampling, fabricating, curing and doing unconfined compression test are in compliance with current standards (ASTM D 2166, ASTM D 1633 và TCVN 9403 : 2012).

3.1. Experimental materials
3.1.1. Soil for experiment. Soil samples: Soil samples were taken in the ground at Zone B in Mien Tay Construction University – Ward 3, Vinh Long City, Vinh Long province. Geotechnical investigation report shows that there are 2 layers up to the depth of 22 m in the ground.

Layer 1: Clay mud, dark gray, plastic liquid state to liquid state, thickness of 14.5 m.

Layer 2: Fine sandy clay mud, dark blue gray, dark brown gray, liquid state, thickness of 7.5 m.

The original soil was taken from borehole by plastic tube with a diameter of 76 mm and a length of 800 mm. After sampling up, two ends of sampling tube must be sealed in order to avoid moisture changes. Samples must be numbered according to hole depth. After taken from the expected depth, samples were transported to laboratory of Mien Tay Construction University to conduct experiments of properties including moisture, density, grain distribution, Atterberg limit.

![Figure 1. Drilling for sampling at the site.](image-url)
Table 1. Properties of testing soil

| Type of soil | w ( % ) | γ (kN/m$^3$) | w$_L$ (%) | w$_p$ ( % ) | φ (degree) | c (kN/m$^2$) |
|-------------|--------|-------------|----------|------------|------------|-------------|
| Layer 1     | 56.6   | 16.3        | 50.0     | 33.0       | 4°24'      | 11.6        |
| Layer 2     | 29.4   | 18.7        | 24.0     | 17.4       | 21°18'     | 9.2         |

Table 2. Grain Aggregation of two Soil layers

| Type of soil | Grain aggregation according to TCVN 4198-1995 | Sand (%) | Silt (%) | Clay (%) |
|--------------|-----------------------------------------------|----------|----------|----------|
|              | Particle size (mm) as percentage (%)          |          |          |          |
|              | 2-1                                           | 1-0.5    | 0.5-0.25 | 0.25-0.1 | 0.1-0.05  | 0.05-0.01  | 0.01-0.005 | <0.005 |
| Layer 1      | 1                                              | 5        | 14       | 31       | 8         | 41         |
| Layer 2      | 2                                              | 2        | 4        | 10       | 24        | 29         | 6         | 23     |

3.1.2. Cement. Nghi Son Cement with preeminent properties, meeting the requirements of TCVN 6260 – 2009 is used in experiments.

Figure 2. Nghi Son cement type in the study.

Figure 3. Metal tubes produce a sample of cement soil.

Table 3. Comparison between Nghi Son cement properties and TCVN 6260:2009

| Criteria                                      | Unit         | TCVN 6260 : 2009 (PCP40) | Nghi Son Cement (Average value) |
|----------------------------------------------|--------------|--------------------------|---------------------------------|
| Compressive strength: 3 days ± 45 minutes    | MPa          | ≥ 18                     | 26 ± 1,5                        |
| 28 days ± 8 hours                            |              | ≥ 40                     | 46 ± 2,0                        |
| Setting time:                                 |              |                          |                                 |
| Initial                                       | Minute       | ≥ 45                     | 130 ± 10                        |
| Final                                         |              | ≤ 420                    | 150 ± 10                        |
| Finessness:                                   |              |                          |                                 |
| Cumulation retain 0.09 mm                    | %            | ≤ 10                     | 2 ± 1                           |
| Blaine specific surface                       | cm$^2$/g     | ≥ 2800                   | 4100 ± 100                      |
| Volumetric stability                          | mm           | ≤ 10                     | 1.0 ± 0.5                       |
| SO$_3$ content                                | %            | ≤ 3.5                    | 1.8 ± 0.2                       |

3.2. Experimental equipment

3.2.1. Soil – cement mixer. Soil – Cement mixer consists of mixing bowl, paddle and speed control as shown in Figure 4.

3.2.2. Unconfined compressive strength prototyping equipment

The metal tubes are 40×80 mm in size and are bisected. Before sampling, the inside surface of the tube wall must be scanned with a layer of Paraffin to facilitate the removal of the sample.

3.2.3. Unconfined Compression Test Apparatus. It is used for unconfined compressive strength ($q_u$) compressive stress of a cylindrical sample with the height of two times the failure diameter. Axial stress is the only force applying on sample until it is failed in the short time provided that water can not enter or exit the sample. During the experiment, results are recorded to the computer until sample...
is failed or deformed to 15% of the sample height when force gauge stopped and gradually decreased the value.

**Figure 4.** Soil – cement mixer. **Figure 5.** Unconfined Compression test Apparatus.

Readings of force (P) are taken from the proving ring dial gause and stress applied to the ends of the sample is computed as follows:

\[
\sigma_1 = \frac{P}{A}
\]

(1)

Where \( A \) is the cross-sectional area of the sample. Because the soil sample height decreases during shear and the volume of the sample remain constant, the cross sectional area must increase. The equivalent or average area (A) at any strain (\( \varepsilon \)) is computed from the initial area (\( A_0 \)) and the assumption that volume is conserved:

\[
A = \frac{A_0}{1 + \varepsilon}
\]

(2)

The unconfined compressive strength (\( q_u \)) is the maximum value \( \sigma_1 \), which may or may not coincide with maximum force measurement (depending on the area correction).

The chart in which the maximum axial stress (\( q_u \)) is determined is drawn from the record.

### 3.3. Experimental procedure

#### 3.3.1. Number of samples

Using the wet mixing method with cement/soil contents in the following cases: 150 kg/m\(^3\) (UC1), 200 kg/m\(^3\) (UC2) and 250 kg/m\(^3\) (UC3).

**Table 4.** Number of samples is used for experiment

| Soilcrete sample | Cement content (Ac) | 7 days | 14 days | 28 days | 60 days |
|------------------|---------------------|--------|---------|---------|---------|
| UC1              | 150kg/m\(^3\)       | 3 samples | 3 samples | 3 samples | 3 samples |
| UC2              | 200kg/m\(^3\)       | 3 samples | 3 samples | 3 samples | 3 samples |
| UC3              | 250kg/m\(^3\)       | 3 samples | 3 samples | 3 samples | 3 samples |

Total: 36 samples \( \times 2 \) (Soil layer) = 72 samples

The total number of samples to be prepared for both layers is 72.

#### 3.3.2. Preparation of samples

**Mixing Soil – Cement sample.** Firstly, sample is taken out of the tube to determine the moisture content, weight of the soil sample as a basis for determining the amount of cement needed for that soil sample. Soil and cement mixture is pour into a mixing bowl. Then, the mixing bowl is attached to the mixer, adjust the rotation speed to mix well. After mixing, the cement and soil are considered homogeneous to a mixture of soil - cement, in other words, the cement and soil particles are distributed relatively evenly over a volume unit.

**Sampling.** When soil and cement are thoroughly mixed, stop mixing and start forming samples. The metal tubes are scanned with a layer of paraffin inside to facilitate sample removal. The soil and cement containers are then covered with a wet cloth to maintain the moisture content of the samples, preventing the sample from drying out. The sample is taken into the metal tube by hand. It is plastered around the wall first, then from the middle of the tube to the ends to limit the sample from pitting.
when removing the mold. Next, the core of the soil cement sample is created. After compacted, the sample is cut at the two ends by a knife then must be sealed with plastic wrap. Every sample is marked then put in a foam container and covered with a wet cloth. Then close the lid of the container, ensuring proper humidity. The process of preparation and curing of samples was carried out at the experiment and environment center – Mien Tay Construction University.

3.3.3. Compression test. Unconfined compressive test: the sample must be tested as soon as taking sample out of curing container. Two sides of sample are plane. Place the sample on the lower cutting board in the center of the compression shaft of the compressor. When the upper table is close to the sample, adjust the spherical base to allow uniform contact, adjust the strain gauge and force gauge to position 0. Apply load at a rate of 10 -15 N / s for samples. Record all readings for each sample. When the sample is damaged, record the failure force and value on the strain gauge, measuring the slope angle of the specimen.

Samples were tested in accordance with TCVN 9403: 2012 standard "Strengthening weak soil base - method of soil cement pile” at the Geological Laboratory belonging to Faculty of Geology and Petroleum Engineering of Ho Chi Minh City University of Technology.

4. Results
A total of 72 samples were tested at 7 days, 14 days, 28 days and 60 days of curing. Mechanical properties of sample such as: compressive strength ($q_u$), elastic module ($E_{50}$) were determined through unconfined compressive test. Since, the relationships of physical and mechanical characteristics were built.

4.1. Data of unconfined compressive test ($q_u$) according to cement content ($A_c$) and curing time ($t$).

Results are presented in Tables 5 and in Figure from 7 to 10.

**Table 5. Results of unconfined compressive test ($q_u$) (Average value)**

| $A_c$ ($kg/m^3$) | Curing duration | $q_u$ ($kN/m^2$) | $q_u$ ($kN/m^2$) | $q_u$ ($kN/m^2$) | $q_u$ ($kN/m^2$) |
|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  | Soil layer 1    | 7 days          | 14 days         | 28 days         | 60 days         |
| 150 kg/m$^3$     | Soil layer 1    | 1068            | 1637            | 2282            | 2375            |
|                  | Soil layer 2    | 1606            | 2094            | 2327            | 2508            |
| 200 kg/m$^3$     | Soil layer 1    | 1750            | 2732            | 3224            | 3309            |
|                  | Soil layer 2    | 2662            | 2911            | 3568            | 3645            |
| 250 kg/m$^3$     | Soil layer 1    | 2276            | 3243            | 3867            | 3928            |
|                  | Soil layer 2    | 3370            | 3922            | 4675            | 4832            |

**Figure 7. Unconfined compressive strength – strain of laboratory stabilized soil (7 days, Soil layer 1)**
Figure 8. Unconfined compressive strength–strain of laboratory stabilized soil (60 days, Soil layer 1)

Figure 9. Unconfined compressive strength–strain of laboratory stabilized soil (7 days, Soil layer 2)

Figure 10. Unconfined compressive strength–strain of laboratory stabilized soil (60 days, Soil layer 2)

4.2. Relationship between strength $q_u$ and curing time ($t$)

Relationship between strength $q_u$ and curing time ($t$), for different soil layer and cement content is shown in Figure 11 and Figure 12.

Figure 11. Unconfined strength $q_u$ with curing duration of two soil layers.
4.3. Relationship between strength $q_u$ and cement content ($A_c$)

Relationship between strength $q_u$ and cement content ($A_c$) of the soil layer 1 and the soil layer 2 is presented in Figure 13. Comparing the two soil layers, the higher the cement content is, the greater the compression strength value gets.

![Figure 13](image)

Figure 13. The relationship between $q_u$ and $A_c$ of the soil layer 1 and the soil layer 2.

4.4. Relationship between strength $q_u$ and 2 soil layers

Relationship between strength $q_u$ and curing time ($t$) for the two soil layers are shown in Figure 14 and Figure 15. The study of unconfined compressive strength for each soil layer is helpful for adjusting cement content for each layer. Therefore, the optimal cost when executing soil-cement piles on site can be achieved.

![Figure 14](image)

Figure 14. The correlation between $q_u$ and curing time has the same cement content.
With the same cement content and the same curing time, the unconfined compressive strength ($q_u$) of soil layer 2 is greater than those of soil layer 1.

4.5. Relationship between strength $q_u$ and secant elastic module ($E_{50}$)

Relationship between strength $q_u$ and secant elastic module ($E_{50}$) is shown in Figure 16.

5. Discussion

With the same time of curing, soil of the layer 2 (Silty Clay with fine sand) gave greater compressive strength than soil of the layer 1 (Clay mud). The reason is that soil layer 2 has more coarse grain content so its strength is higher, that are similar to some previous research results [20].

The unconfined compressive strength ($q_u$) of most samples increases over curing time, that are similar to those of [17,18]. The strength of mixing increases during curing because of the hydration reaction of cement and pozzolanic reaction over time, which can last for months or a year after [19]. Curing periods as follows: Soil of layer 1 with the cement content of 150 kg/m$^3$ is cured from 7 to 28 days, the compressive strength $q_u$ increases by 113.67% while it is cured from 7 to 60 days, the compressive strength $q_u$ increases by 122.38%. Do the same experiment with soil of layer 2, the compressive strength $q_u$ increases by 44.89% and 56.16% respectively.

Understanding of the relationship between compressive strength $q_u$ and curing time is meaningful in determining the time when soilcrete reaches sufficient strength before put into use. In addition, unconfined compressive strength at 28 days ($q_{u28}$) and those at other points of time are inferred from above results. Specifically the relationship between impressive strength at 7 days ($q_{u7}$), 14 days ($q_{u14}$) and 60 days ($q_{u60}$) and unconfined compressive strength at 28 days ($q_{u28}$) are shown in Figure 17. The unconfined compressive strength at any time can be predicted by interpolating or extrapolating.
Compressive strength $q_u$ increases with cement content, that are similar to those of [17,18]. Cement content as follows: when sample of Layer 1 is cured at 7 days, cement content increases from 150 kg/m$^3$ to 200 kg/m$^3$, the compressive strength $q_u$ increases by 63.9% while cement content increases from 150 kg/m$^3$ to 250 kg/m$^3$, the compressive strength $q_u$ increases by 113%. Do the same experiment with soil of layer 2, the unconfined compressive strength $q_u$ increases by 65.8 % and 109.8% respectively.

Secant elastic module ($E_{50}$) increases as unconfined compressive strength increases. The relationship between unconfined compressive strength and secant elastic modulus ($E_{50}$): Cement – soil samples of layer 1 reached 96.6$q_u$ and Cement- soil samples of layer 2 reached 72.1 $q_u$, as shown in Figure 16. Secant elastic modulus ($E_{50}$) is determined from the relationship with $q_u$ to evaluate the resistance of deformation of the ground. Therefore, the preliminary quality of soil – cement can be known.

6. Conclusions
The soil was sampled to a depth of 22.0 m in Zone B of Mien Tay Construction University - Ward 3, Vinh Long City, Vinh Long Province, has 2 layers. Soils of Layer 1 and Layer 2 are mixed with cement to form a mixture of soil - cement samples for research. Unconfined compression tests are done with 3 cement contents of 150 kg/m$^3$, 200 kg/m$^3$ and 250 kg/m$^3$ at 7 days, 14 days, 28 days and 60 days. Each soil layer was prepared with 36 cylindrical samples of size $d \times h = 40$ mm $\times$ 80 mm. Experimental results show that:

Strength of most soil-cement samples increased over curing time. Soil of Layer 1 with the cement content of 150 kg/m$^3$ is cured from 7 to 28 days, the unconfined compressive strength ($q_u$) increases by 113.67% while it is cured from 7 to 60 days, the unconfined compressive strength ($q_u$) increases by 122.38%. Do the same experiment with soil of layer 2, the unconfined compressive strength ($q_u$) increases by 44.89% and 56.16% respectively.

At the same curing process, the strength of cement- soil samples of Layer 2 greater than those of Layer 1. The study of unconfined compressive strength for each soil layer can adjust the cement content for each soil layer in order to achieve the optimal cost when executing soil cement piles in the field.

Strength of soil samples of soil-cement mixer increased rapidly during the period of 14 to 28 days of age. The increase of unconfined compressive strength ($q_u$) is involved with the time (t) of each cement content ($A_c$) in the laboratory is expressed through the following expressions:

Layer 1:
- $A_c = 150$ kg/m$^3$: $q_u = 0.6352\ln(t) - 0.0669$
- $A_c = 200$ kg/m$^3$: $q_u = 0.7177\ln(t) + 0.5985$
- $A_c = 250$ kg/m$^3$: $q_u = 0.7748\ln(t) + 1.0018$

Layer 2:
- $A_c = 150$ kg/m$^3$: $q_u = 0.4097\ln(t) + 0.9035$
- $A_c = 200$ kg/m$^3$: $q_u = 0.5024\ln(t) + 1.6879$
- $A_c = 250$ kg/m$^3$: $q_u = 0.7058\ln(t) + 2.0979$

Secant elastic modulus ($E_{50}$) increases when the unconfined compressive strength ($q_u$) increases. The value of unconfined compressive strength can determine the secant elastic modulus of the stabilized soil sample. According to the experimental results, one propose here is $E_{50} = 96.6q_u$ (for...
layer 1) and $E_{50} = 72.1\text{q}_u$ (for layer 2). Secant elastic module ($E_{50}$) is determined from the relationship with $\text{q}_u$, showing the resistance to the deformation of the ground. Thus, the preliminary evaluation of the quality of soil – cement piles are estimated.

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