Direct Shear Behavior of Nanometer Magnesia Reinforced Cement Soil with 28d Age

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Abstract: In order to properly understand the modification effects of nanometer magnesia additive on cement soil mechanical performance, a consolidated quick shear laboratory test on nano-magnesium-modified cement-soil (NmCS) sample with different mixing ratio at 28-day age was conducted. Eight kinds’ of nanometer magnesia additives with mixing ratios ranging from 0% to 3% were designed to take into the test. The result shows that: (1) shear stress-displacement curves of all samples consist of three distinct stages with brittle failure; (2) with the nanometer magnesia mixing ratio increase, the NmCS shear strength shows an increase at first and then a decrease, and the shear strength reaches the maximum with the mixing ratio of 1%; (3) both the friction angle and cohesive force are a fluctuating and show a concave and convex shape respectively; (4) with greater deformation resistance, the shear displacement of NmCS is significantly less than the ordinary cement soil in the shear failure process. Finally, according to the test results, the micro-mechanism of NmCS mechanical performance was analyzed from the perspective of cement hydration and particle interaction.

Keywords: Cement stabilized soil, nanometer magnesia, mixing ratio, shear strength.

1. INTRODUCTION

With obvious comprehensive benefits by the application of foundation treatment technology, cement stabilized soil has been widely applied to the practical engineering construction such as foundation reinforcement of various types of buildings, roads, railways, airports, and etc.; building envelopes and water-resisting curtains of the excavation process; foundation reinforcement and seepage of various large water conservancy dams; and road base material and impermeable lining material. In the engineering practice, however, there are some problems such as cement soil strength is not high with large deformation of composite foundation in the later process, which restricts the further application of this technology [1, 2]. It is a very important study to find out an admixture with high modification effect to improve the cement soil strength.

Currently, silica ash, fly ash and other common ultra-fine mineral powder have been widely used to increase the performance of concrete, cement soil and other cement-based materials, which have obtained certain engineering utilizations. Scientific research shows that when the substances are processed below to 100nm size, extraordinary properties will be produced which are different not only from the microscopic atoms and molecules, but also from the macroscopic perspective. This excellent feature is called “nano effect” [3-7]. With the popularity of nano products and people’s recognition of its performance and quality, nano materials have been well developed and industrialized production has been started for some. Nano mineral powder particle size is between 1~100nm with outstanding features such as large specific surface area and unsaturated surface atoms coordination. Therefore, mixing nano mineral powder with finer particles and larger specific surface area and higher activity into cement soil is being explored [8-11]. Nano-MgO is a new high-performance fine inorganic material with optical, electrical, magnetic and chemical properties which has been widely applied to the field of electronics, catalysis, ceramics, antibacterial and buildings [12, 13].

In this paper, industrialized production of nano-MgO has been taken as the cement soil admixture to study its modification effect on the cement soil, explored the shear strength and deformation of nano-magnesium-modified cement-soil (hereinafter referred to as: “NmCS”), analyzed and evaluated the nano-MgO modification effect on cement soil, thus carried out the research and exploration for the application to engineering practice.

2. MATERIALS AND METHODOLOGY

Clay soil with low liquid which are widely distributed in the eastern coastal area of China were taken as the test soil,
and samples were taken from Qingliangshan, Nanjing City, Jiangsu Province, with 30% moisture content, 1.9 g/cm³ wet density, 2.69 specific gravity of soil particles, 43% liquid limit, 20% plastic limit, and 23 plasticity index; 11.5kPa cohesion and 15.2° friction angle in the consolidation quick direct shear process.

P.C 32.5# Composite Portland Cement produced by Nanjing Conch Cement Co., Ltd., and Nano-MgO produced by Aladdin Industrial Corporation were taken in this experiment.

The soil samples were prepared by drying and crushing, and sifting over a diameter of 2mm sieve. Prepare the test sample by the designed ratio. In the preparation process, soil samples, cement and Nano-MgO with specified amount were sealed in a closed container, stirring for 8 minutes until evenly mixed, and then use a water kettle to uniformly spray it, and continue stirring the mixture evenly until the required moisture and humidity is reached. The wet soil moisture content was 30% and ratio between cement and wet soil quality was 10%. Compared with the soil cement, eight kinds of Nano-MgO mixing ratios were taken as 0%, 0.25%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5% and 3.0%.

Shear samples were with 6.18cm diameter, 2cm height, and (1.98±0.02) g/cm³ sample density. Four normal stresses were considered in the direct shear test. In order to prevent the sample damage, five samples were prepared in each group including a spare; being cured to 28d age in the curing box, and then the consolidated quick shear test was conducted.

During the test, the sample was consolidated initially and shear test can be conducted after 24h. In the shearing process, pulled out the fixed pin, immediately sheared with 0.8mm/min shear rate, samples were with shear failure in 4min–6min. Before the shearing failure, the shear stress shown on the instrument was recorded per 0.2mm shear displacement; while after the sample failure, per 0.1mm shear displacement. Shearing was continued after samples failure with peak shearing stress until the instruments reading was stable.

3. RESULTS AND ANALYSIS

3.1. Failure Characteristics

In the consolidation quick direct shear process of nano-MgO cement soil with different mixing ratio, the shear displacements are less than 1mm with brittle failure. Failure processes are basically the same for each sample. At 28d age with mixing ratio aw=1.0%, the relations between shear stress τ and shear displacement Δ of NmCS are shown in Fig. (1). There are 3 distinct phases presented in the shearing process:

Phase ①: Before shear failure, with the shear displacement increase, the shear stress τ shows a linear increase. When the shear stress τ ≤ 0.7τmax (τmax is the peak shear stress), τ-Δ relations are with linear variation; When the shear stress τ > 0.7τmax, displacement growth rate becomes higher than the stress growth rate, shear stress produces plastic deformation until stress-deformation curve reaches the peak point.

Phase ②: During shear failure, when the data shown on the instrument reaches the maximum, the samples are suddenly sheared broken and the data instantly decreases to a minimum. NmCS samples are with brittle failure under different normal stress.

Phase ③: After shear failure, with the continuing increase of shear displacement Δ, the shear stress τ still increases. After a period of increase, the shear stress tends to be stable; the residual shear stress is much less than the peak shear stress.

As can be seen from Table 1, under different normal stress, the shear strength variation of the NmCS is roughly the same, and the shear strength τ first increases and then decreases with the Nano-MgO mixing ratio aw. When aw=1.0%, the NmCS shear strength maximum can reach to 646kPa, 714kPa, 757kPa and 803kPa respectively under different normal stress, which are 1.90 times, 1.63 times, 1.38 times and 1.26 times that of the ordinary cement soil in the same period. With the mixing ratio continuous increase,
NmCS shear strength shows continuous decrease, but its strength value is still greater than the strength of ordinary cement soil. According to Table 1, we can get fitting curves of the shear strength of NmCS under different normal stress by the following fitting equation:

\[
\begin{align*}
\tau_{100} &= 33.7a_w^3 - 255.0a_w^2 + 72.5a_w + 300.0 \\
\tau_{200} &= 46.6a_w^3 - 298.7a_w^2 + 491.5a_w + 414.2 \\
\tau_{300} &= 41.8a_w^3 - 268.8a_w^2 + 444.4a_w + 513.0 \\
\tau_{400} &= 30.8a_w^3 - 195.8a_w^2 + 320.6a_w + 626.8
\end{align*}
\]  

(1)

In the equation, \(\tau_{100}, \tau_{200}, \tau_{300}\), and \(\tau_{400}\) are the NmCS shear strength under normal stress 100kPa, 200kPa, 300kPa and 400 kPa.

### 3.3. Cohesion and Friction Angle

With different nano-MgO mixing ratios, the shear strength and the normal stress of NmCS samples show a linear relation which complies with Moore Coulomb criterion. The measured data and fitting data with three typical mixing ratios are shown in Fig. (2).

\[
\tau_f = c + \sigma \tan \phi
\]  

(2)

In the equation, \(c\) is the cohesion and \(\phi\) is the friction angle.

![Fig. (2). Relations between Normal Stress and Shear Strength.](image)

According to the equation (2) and Table 1, \(\phi\) and \(c\) of NmCS are calculated and curves drawn in Figs. (3, 4). As can be seen from Figs. (3, 4), with the increase of nano-MgO mixing ratio \(a_w\), the friction angle \(\phi\) and cohesion \(c\) show fluctuating variation with concave and convex shape respectively. When \(a_w=1.0\%), \phi\) and \(c\) are up to their maximum value and the minimum value respectively.

### 3.4. Deformation Characteristics

It is found that NmCS has a better deformation resistance than ordinary cement soil. According to phase ① in Fig. (1), take \(a_w\) as 0% and 1.0% and shear displacement of 0.4mm for example; the shear stress are shown in Table 2. As can be seen from Table 2, NmCS has greater deformation resistance with same shear displacement. The shear stress it can withstand is significantly higher than ordinary cement soil with the same displacement, when normal stresses are 100kPa, 200kPa, 300kPa and 400kPa. The shear stress of NmCS are 1.9 times, 1.5 times, 1.2 times, 1.2 times that of the normal cement soil.

![Fig. (3). Friction Angles of NmCS with Different nano-MgO Ratio.](image)

![Fig. (4). Cohesion of NmCS with Different nano-MgO Ratio.](image)

### Table 2. Shear stress at 0.4mm shear displacement/kPa.

<table>
<thead>
<tr>
<th>(a_w) (%)</th>
<th>Normal Stress/ kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>100 274 200 320 300 434</td>
</tr>
<tr>
<td>1.00</td>
<td>512 468 464 520</td>
</tr>
</tbody>
</table>

If applied to cement mixing pile, NmCS pile with nano-MgO admixture under the action of transverse shear force will produce smaller shear displacement. It is more stable which can greatly improve critical force of the compression bar compared with ordinary cement pile. Its strength is higher than NmCS pile. Therefore, it has much wider application than ordinary cement pile.

Based on the above analysis, with more mechanical properties improvement, NmCS with 1% nano-MgO mixing ratio is taken as the best ratio.
4. NmCS CURING MECHANISM ANALYSIS

MgO is an alkaline oxide which absorbs moisture and carbon dioxide easily to produce basic magnesium carbonate when exposed to air. MgO has hygroscopicity with a certain relation to the size of the surface area, the larger the surface area higher the hygroscopicity. Therefore, the Nanoscale MgO surface is with super-hydrophilic property. Water adsorbed by surface can be dissociated by the reaction and easy to form chemical adsorbed water, forming a physical adsorbed layer. Thus, nano-MgO mixed in the cement can quickly adsorb Ca^{2+} ions in the liquid phase to form small crystalline state Ca(OH)_{2} to accelerate the hydration rate of C3S, which can improve the rate of hydration of cement particles to form a more compact calcium silicate hydrate gel structure. Meanwhile, NmCS has a more uniform and dense microstructure. Nano-MgO filling effect is an important factor in improving cement stabilized soil microstructure. Nano-MgO mixed in cement paste is used to fill the pores of hydration products to make the cement structure denser [1].

Concluded, nano-MgO with properties of small particle, large specific surface area and is super-hydrophilic. When mixed with soil, it can be adsorbed on the soil surface, thus becoming the core of calcium silicate hydrate gel produced by normal cement hydration, so that the calcium silicate hydrate gel can be preferably knotted together with compact structure. The nano-MgO mixed in the cement soil also has equal filling effect on the cement soil. It can reduce the number of pores and refine the soil cement pore size. The larger soil aggregates can be further combined to close the gap between each soil group and join together to form the overall improvement of the microstructure of cement to improve the strength properties [9]. Thus, NmCS strength will be significantly improved with a suitable mixing ratio.

5. RESULTS AND DISCUSSION

According to the quick direct shear test of NmCS with different mixing ratio with 28d age, preliminary conclusions are as follows:

(1) When the nano-MgO mixing ratio aw=1% under the normal stress of 100kPa, 200kPa, 300kPa and 400kPa, the shear strength of NmCS are 1.90 times, 1.63 times, 1.38 times and 1.26 times that of the ordinary cement soil, respectively;
(2) When the normal stress are 100kPa, 200kPa, 300kPa and 400kPa and with shear displacement of 0.4mm, NmCS shear stress are 1.9 times, 1.5 times, 1.2 times, 1.2 times that of ordinary cement soil, respectively;
(3) When nano-MgO mixing ratio is relatively small, the growth rate of NmCS strength is relatively large; when mixing ratio exceeds a certain value, the growth rate begins to decline.

Although nano-MgO as admixture shows excellent enhancement effect in this study, there are still further researches need to be further processed:

(1) Clay soil with low liquid as the test soil samples are taken from Qingliangshan, Nanjing City, Jiangsu Province. With the nano-MgO mixing ratio increase, the NmCS shear strength of each vertical stress increases first then decreases and then increases again. This variation mechanism may be varying with different original soil components which need further experimental and theoretical exploration.

(2) Composite Portland cement taken in the experiment is green building materials which contains mixed material, with stable strength in the early and late stage and low heat of hydration. It is an economical cement which is suitable for general industrial and civil construction application. The total mixing ratio of the hybrid material is by mass ratio range 20%~50% with not very high Portland cement clinker content, it may result in nano-MgO limited effect on the soil cement. That is different from the ordinary Portland cement taken in the cement soil study conducted by Zhu [8] and Wang [9]. Later, ordinary Portland cement will be taken to do the comparison test to explore the relations between the strength improvement and environment protection.

(3) NmCS strength depends on the structure of the gel material and connection between the gel material and soil particles. Nano-MgO admixture can enhance cement gel material structure to reduce cement soil porosity and improve connection between the gel material and soil particles. Interactions between nano-MgO and soil remains to be explored further, with the continuous advances in Nanotechnology, comprehensive benefits of nano-MgO application to soil cement and other cement-based materials will provide a broad space for the transformation of traditional industries.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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