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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's 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 be used in the test. The result shows that: (1) shear stress-displacement curves of all samples consisted of three distinct stages with brittle failure. Moreover, (2) as the nanometer magnesia mixing ratio increased, the NmCS shear strength also showed an increase at first, followed by a decrease, and the shear strength reached the maximum with the mixing ratio of 1%. (3)In addition, both the friction angle and cohesive force were fluctuating and had a concave and convex shape respectively and (4) with greater deformation resistance, the shear displacement of NmCS was 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 of 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's 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 been utilized in the field of engineering. 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 materials. Nano mineral powder particle size varies 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 was taken as the cement soil admixture to study its modification effect on the cement soil, to explore the shear strength and deformation of nano-magnesium-modified cement-soil (hereinafter referred to as: "NmCS"), analyze and evaluate the nano-MgO modification effect on cement soil. Thus the research and exploration was carried out for the application in engineering practice.

2. MATERIALS AND METHODOLOGY

Clay soils with low liquid which are widely distributed in the eastern coastal area of China were taken as the test soil,

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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; with 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 used in this experiment.

The soil samples were prepared by drying and crushing, and sifting over a diameter of 2mm sieve. The test sample was prepared 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 a water kettle was used to uniformly spray the soil, and stirring of the mixture was continued evenly until the required moisture and humidity were achieved . 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 of 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, followed by the consolidated quick shear test .

During the test, the sample was consolidated initially and shear test was conducted after 24h. In the shearing process, the fixed pin was pulled out and immediately sheared with 0.8mm/min shear rate. The samples with shear failure were obtained 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, it was per 0.1mm shear displacement. Shearing was continued after samples' failure with peak shearing stress until the instruments reading became stable.

3. RESULTS AND ANALYSIS

3.1. Failure Characteristics

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

Phase ①: Before shear failure, with increase in the shear displacement, the shear stress τ showed a linear increase. When the shear stress $\tau \leq 0.7\tau_{max}$ (τ_{max} is the peak shear stress), τ-Δ relations had linear variation. When the shear stress τ>0.7τmax, displacement growth rate became higher than the stress growth rate, and shear stress produced plastic deformation until stress-deformation curve reached the peak point.

Phase ②: During shear failure, when the data shown on the instrument reached the maximum, the samples were suddenly sheared broken and the data instantly decreased to a minimum. NmCS samples showed brittle failure under different normal stress.

Phase ③: After shear failure, with continued increase in the shear displacement Δ, the shear stress τ still increased. After a period of increase, the shear stress became stable while the residual shear stress became less than the peak shear stress.

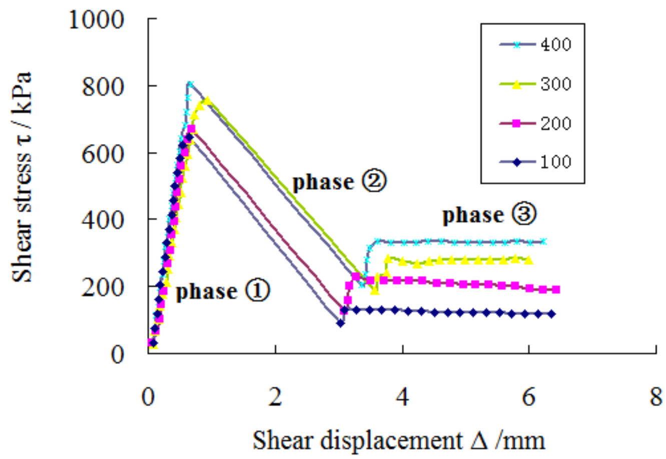

Fig. (1). Shear stress-displacement curves of NmCS.

3.2. Shear Strength

The peak stress in the τ-Δ curves is taken as the shear strength. The experimental results of shear strength of each NmCS sample are shown in Table **1**.

Table 1. Investigated shear strength of NmCS / kPa.

a_w	Normal Stress/ kPa			
/(%)	100	200	300	400
0.00	339	438	547	638
0.25	370	505	573	688
0.50	409	541	642	721
1.00	646	714	757	803
1.50	539	624	745	777
2.00	452	569	647	720
2.50	434	497	574	686
3.00	332	463	568	661

As can be seen from Table **1**, under different normal stresses, the shear strength variation of the NmCS was roughly the same, and the shear strength τ first increased and then decreased with the Nano-MgO mixing ratio aw. When a_w=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 continuous increase in the mixing ratio , NmCS shear strength showed continuous decrease, but its strength value was still greater than the strength of ordinary cement soil. According to Table **1**, the fitting curves of the shear strength of NmCS were obtained under different normal stress by the following fitting equation:

$$\begin{cases} \tau_{100} = 33.7a_w^3 - 255.0a_w^2 + 72.5a_w + 300.0 \\ \tau_{200} = 46.6a_w^3 - 298.7a_w^2 + 491.5a_w + 414.2 \\ \tau_{300} = 41.8a_w^3 - 268.8a_w^2 + 444.4a_w + 513.0 \\ \tau_{400} = 30.8a_w^3 - 195.8a_w^2 + 320.6a_w + 626.8 \end{cases} \quad (1)$$

In the equation, τ_{100}, τ_{200}, τ_{300}, and τ_{400} are the NmCS shear strength under normal stress100kPa, 200kPa, 300kPa and 400 kPa respectively.

3.3. Cohesion and Friction Angle

With different nano-MgO mixing ratios, the shear strength and the normal stress of NmCS samples showed 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**).

$$\tau_f = c + \sigma \tan\varphi \quad (2)$$

In the equation, c is the cohesion and φ is the friction angle.

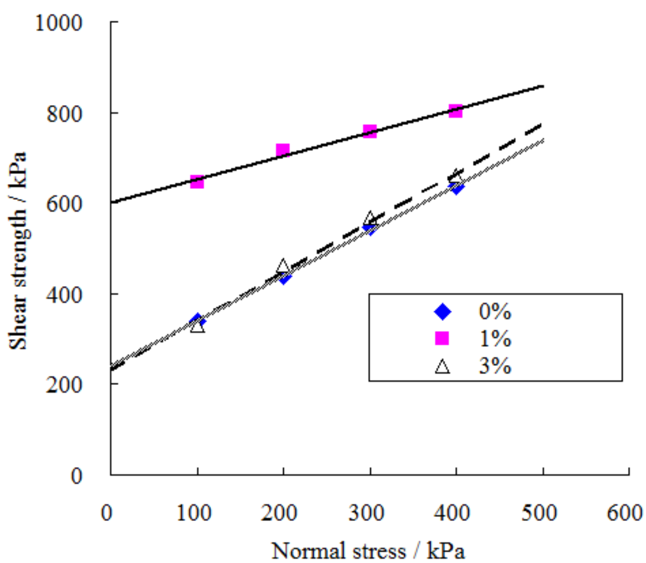

Fig. (2). Relations between Normal Stress and Shear Strength.

According to equation (2) and Table **1**, φ and c of NmCS were calculated and curves were drawn as shown in Figs. (**3**, **4**). As can be seen from Figs. (**3**, **4**), with increase in nano-MgO mixing ration aw, the friction angle φ and cohesion c showed fluctuating variation with concave and convex shape respectively. When aw=1.0%, φ and c were up to their maximum value and the minimum value respectively.

3.4. Deformation Characteristics

It was found that NmCS exhibited a better deformation resistance than ordinary cement soil. According to phase ① in Fig. (**1**), by taking aw 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 had greater deformation resistance with same shear displacement. The shear stress it can withstand is significantly higher than the ordinary cement soil with the same displacement, when normal stresses are 100kPa, 200kPa, 300kPa and 400kPa. The shear stress of NmCS was 1.9 times, 1.5 times, 1.2 times, 1.2 times that of the normal cement soil.

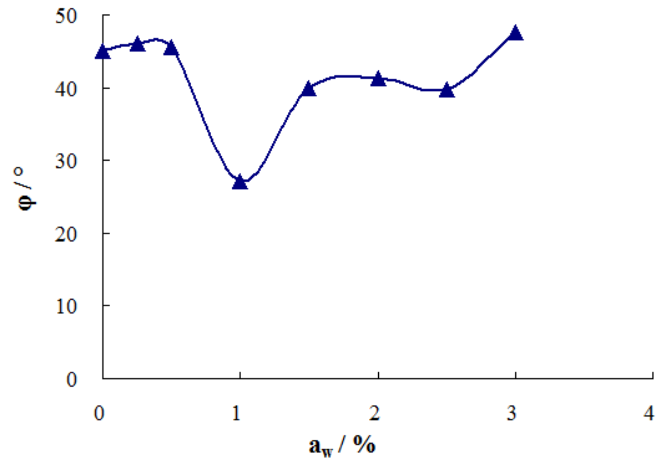

Fig. (3). Friction Angles of NmCS with Different nano-MgO Ratio.

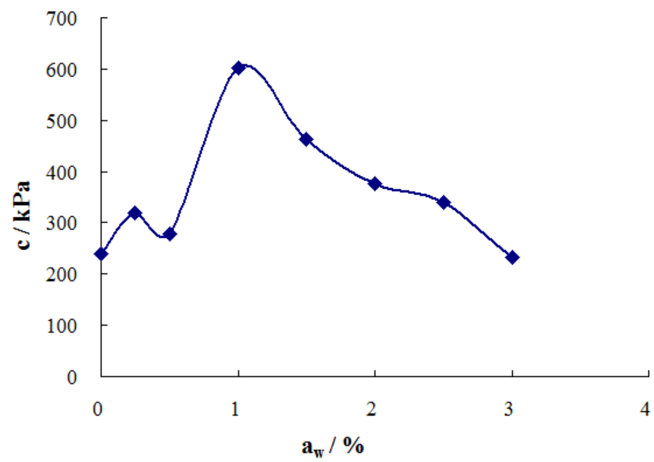

Fig. (4). Cohesion of NmCS with Different nano-MgO Ratio.

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

a_w	Normal Stress/ kPa			
/(%)	100	200	300	400
0.00	274	320	390	434
1.00	512	468	464	520

If applied to cement mixing pile, NmCS pile with nano-MgO admixture under the action of transverse shear force produces smaller shear displacement. It is more stable which can greatly improve critical force of the compression bar compared with the 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 considered 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, suggesting that the larger the surface area, the higher the hygroscopicity. Therefore, the Nanoscale MgO surface has super-hydrophilic property. Water adsorbed by surface can be dissociated by the reaction which makes it easy to form chemically adsorbed water, forming a physically 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 affect is an important factor in improving cement-stabilized soil's microstructure. Nano-MgO mixed in cement paste is used to fill the pores of hydration products to make the cement structure denser [1].

To conclude, nano-MgO is characterized by the 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 similar 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 overall improve the microstructure of cement to enhance their strength [9]. Thus, NmCS's strength will significantly be improved with a suitable mixing ratio.

5. RESULTS AND DISCUSSION

According to the quick direct shear test of NmCS with different mixing ratios 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 was 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 was 100kPa, 200kPa, 300kPa and 400kPa and with shear displacement of 0.4mm, NmCS shear stress was 1.9 times, 1.5 times, 1.2 times, 1.2 times than that of ordinary cement soil, respectively;

(3) When nano-MgO mixing ratio was relatively small, the growth rate of NmCS strength was relatively increased, however, when mixing ratio exceeded to a certain value, the growth rate began to decline.

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

(1) Clay soils with low liquid as the test soil samples were taken from Qingliangshan, Nanjing City, Jiangsu Province. With increase in the the nano-MgO's mixing ratio, the NmCS shear strength of each vertical stress increased first then decreased and again increased . 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 was green building materials which contains mixed material, with stable strength in the early and late stage having 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 by mass ratio ranges from 20%~50% with not very high Portland cement clinker content, which may result in creating limited effect of nano-MgO on the soil cement. This is different from the ordinary Portland cement used in the cement soil study conducted by Zhu [8] and Wang [9]. Later, ordinary Portland cement will be taken for the comparison 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 remain to be explored further. With 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.

ACKNOWLEDGEMENTS

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