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EXPERIMENTAL STUDY OF NANOMETER MAGNESIUM OXIDE-MODIFIED CLAY

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Lei Gao, Zhen Ren, and Xiangjuan Yu
Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Research Institute of Geotechnical Engineering, Hohai University, Nanjing, Jiangsu 210098, China

Nanometer magnesium oxide (NM) is used as a new type of additive for clay. Laboratory tests were performed on clay samples to study the mechanism of NM soil reinforcement. Different NM contents (0%, 1%, 2%, 3%, 4%, and 6% by weight of clay) were freely added to the soil samples, which included different water contents (10%, 16%, and 22%). Eighteen samples were prepared, and unconfined compressive strength tests were carried out. The results show that the unconfined compressive strength of the soil samples increases with NM content and decreases with higher soil water content. The addition of 6% NM to clay soil can significantly improve the strength and stability of the soil. Our study shows that NM can increase the cementation, pore filling, and water sorption of the soil particles, which contributes to significant enhancement of the solidification effect.

The strength of natural clay materials does not always meet the growing demand for strong foundations in modern engineering. Research into clay solidification aims to develop and apply curing materials to help overcome this deficiency to some extent [1-5]. A variety of curing materials for modified clay are in wide use today; these include cement, lime, and fly ash. These curing materials can be divided into three major types based on their composition: inorganic binding materials, ionic soil stabilizers, and composite curing agents. Currently, however, traditional soil curing materials cannot meet all the engineering requirements [6-12]: cement-stabilized soil is restricted by soil type, and the solidification effect is not ideal in clay soil whose plasticity index is high, in organic soil, or in saline soil. The development of limestone soil strength is slow and the water stability is relatively poor; the strength of limestone soil is proportional to the mixing ratio of lime within a certain range, but if the content exceeds this range, the strength is reduced. The initial strength of fly ash lime-stabilized soil is poor, directly affecting the progress and quality of the construction.

Nanomaterials are superfine materials with particle size 1-100 nm. Because of the small particle size, nanomaterials have special structural features, producing four major effects: the size effect, quantum effect (macroscopic quantum tunneling effect), surface effect, and interface effect. Much of today's material science research focuses on nanomaterials, and they have been named as "the most promising materials of the XXI century" [13-20]. Presently, nanomaterials with excellent admixture properties are used to modify cement soil with good results [21-26] but very few studies have been performed on nanomaterials used in clay [27-33]. Research on applying nano-oxide to clay is even scarcer and its reinforcement mechanism is not clear. The effect of the soil water content and the optimal nanomaterial dosage is also unclear; therefore, research on nanomaterial modified clay is particularly important.

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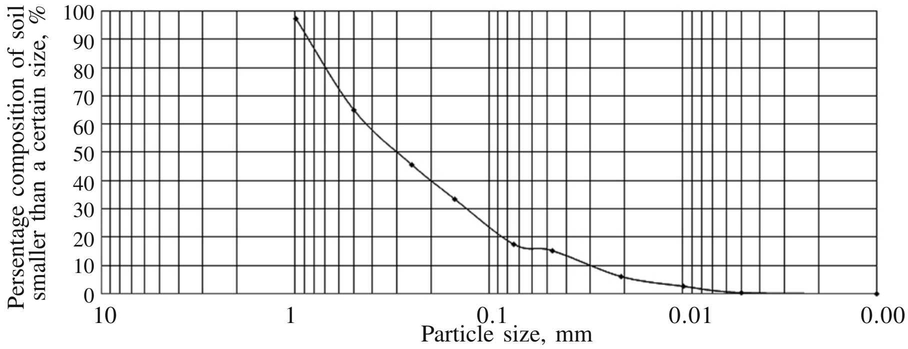

Fig. 1. Results of gradation analysis.

TABLE 1

Number	*w* (%)	Content of NM (%)
S1	10	0
S2	10	1
S3	10	2
S4	10	3
S5	10	4
S6	10	6
S7	16	0
S8	16	1
S9	16	2
S10	16	3
S11	16	4
S12	16	6
S13	22	0
S14	22	1
S15	22	2
S16	22	3
S17	22	4
S18	22	6

In this paper, nano-MgO (referred to as NM) is used to modify the engineering properties of clay. We analyze the effect of NM using unconfined compressive strength tests and explore the mechanisms by which NM improves the clay properties. Based on the analysis of the clay-NM interactions, the curing mechanism of NM for clay is discussed. Our results can provide guidelines for engineering applications to enhance nano-oxide reinforcement of clay.

Materials and testing

The nano-MgO used in the test is produced by Xuancheng Jing Rui New Material Co., China. The NM was supplied as a white powder with a specific surface area of 16 m^2/g and an average grain size of 40 nm. The mass fraction is more than 99.99%, and the pH value is 7.5.

The soil for the tests was taken from a construction site in Nanjing; its physical properties are: liquid limit W_L = 43.6%, plasticity index I_p = 20.3, optimum moisture content w_{opt} = 20.69%, maximum dry density ρ_d = 1.64 g/cm^3, grain percentage = 82.5, 17, and 0.5% for size 2-0.075, 0.075-0.005, and <0.005 mm, respectively, D_{60} = 0.4168 mm, D_{30} = 0.1297 mm, D_{10} = 0.0283 mm, C_u = 14.7, C_c = 1.4.

The grain-size curve (based on a grain-size analysis test) is shown in Fig. 1. It shows that more that 50% of the particles have a particle size greater than 0.075 mm. The analysis showed that the test soil can be classified as low liquid limit clay.

After natural weathering, the soil was crushed (the air-dry soil water content was 3.05%) and soil samples with three levels of soil water content (w = 10%, 16%, and 22%) were prepared in the laboratory. Then, NM was added at six different levels: 0, 1, 2, 3, 4, and 6% of dry soil weight. Altogether, 18 sets of soil samples were prepared according to the above ratio. The related parameters of each sample are listed in Table 1. Each set of three soil samples was prepared for parallel testing using the

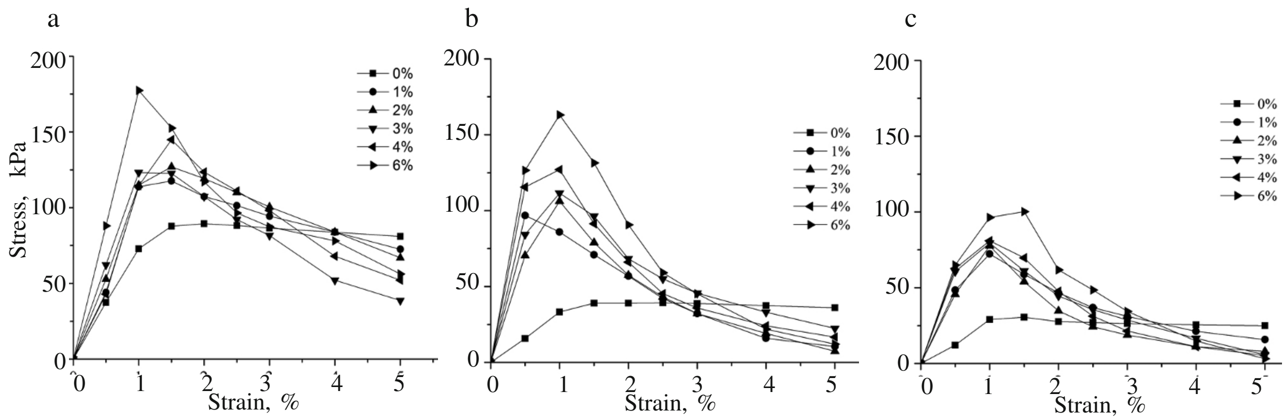

Fig. 2. Stress-strain curves of unconfined compressive strength for soil samples: a) w = 10%, b) w = 16%, c) w = 22%.

pressure-like method. Each sample was 80 mm thick with a diameter of 39.1 mm. The soil samples were saturated by the vacuum saturation method.

To understand the strength of NM modified soil, an unconfined compressive strength (q_u) test was carried out. The q_u of each sample was obtained for all 18 sets of specimens using a YYW-2 strain control unconfined compression tester (Nanjing Soil Instrument Co., Nanjing, China). All the soil samples were fully immersed in water for 24 h before testing. Each sample was loaded at 2.4 mm/min until it reached failure point. The axial strain and axial stress of the soil samples were calculated as follows:

$$\varepsilon = \Delta h / h_0, \tag{1}$$

and

$$\sigma = (CR / A_1) \times 10, \tag{2}$$

where ε is axial strain, σ is axial stress [kPa], C is dynamometer constant coefficient, R is dynamometer reading, A_1 is sample calibration area, 10 is coefficient of unit conversion, Δh is axial deformation, and h_0 is sample initial height.

Results and discussion

Figure 2 shows the stress-strain curve of the soil samples for different NM content in the unconfined compressive strength test. For soil water content of 10%, 16%, and 22%, the axial stress shows two peaks as the axial strain increased. The stress-strain curves of the high-NM-content soil samples are above those of the low-NM-content soil. Initially, the stress-strain curves of the NM clay rise as the NM content increases. After the axial strain develops, the axial stress of the NM clay increases rapidly, the initial stiffness increases, and the slope of the stress-strain curve becomes gradually steeper in the initial period. When the axial stress increases to a certain level, the stress-strain curve reaches a peak, which increases with higher NM content. From the peak, the stress-strain curve slopes down, showing a steeper decline as the NM content of the sample increases.

Our analysis of the unconfined compressive strength test (Table 2) shows that for the soil samples with a soil water content of 10%, 16%, and 22%, the addition of NM significantly enhances the strength of the soil samples, with the highest increase rate reaching 308.08%.

The q_u of the soil samples with the same water content increases with rising NM content; the strength of the soil samples with w = 16% increases most significantly for the sample with NM = 6% (Fig. 3). All the samples with NM = 6% show a considerable increase in soil strength, especially compared with the samples with NM = 4%.

TABLE 2

Number	q_u, kPa	Percentage of the strength increase (%)
S1	90.28	0.00
S2	120.27	33.22
S3	126.35	39.95
S4	129.73	43.70
S5	146.28	62.03
S6	180.63	100.08
S7	40.00	40.00
S8	103.13	103.13
S9	106.45	106.45
S10	110.64	110.64
S11	135.63	135.63
S12	163.23	163.23
S13	31.11	0.00
S14	71.33	129.28
S15	77.33	148.57
S16	78.89	153.58
S17	81.57	162.20
S18	104.44	235.71

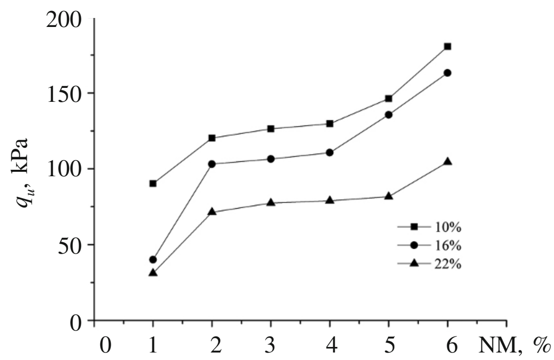

Fig. 3. Effect of NM content on q_u for soil samples.

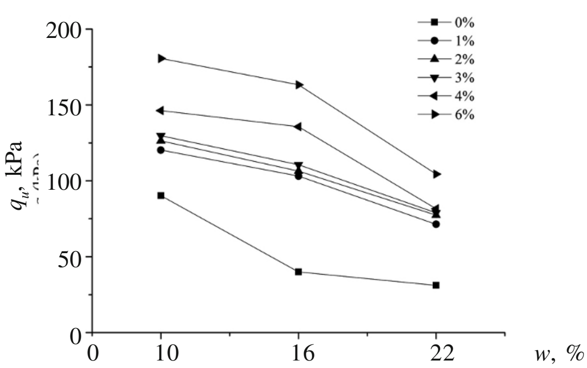

Fig. 4. Effect of soil water content on q_u for soil samples.

For samples S1, S7, and S13, with NM = 0%, the q_u is 90.28, 40.00, and 31.11 kPa, respectively (Table 2 and Fig. 4). After adding 4% of NM, the strength increases to 146.28, 135.63, and 81.57 kPa, showing a growth in strength of 62.03%, 239.08%, and 162.20%, respectively. For the soil samples with 6% NM, the growth in strength is 100.08%, 308.08% and 235.71%. This indicates that the increase in NM content rapidly increases the strength of the soil samples; the rate of strength increase is higher when the soil water content is 16%.

The change in q_u for soil samples with varying soil water content is shown in Fig. 4. The q_u of the soil samples with the same NM content decreases with increasing w, and the magnitude of the change is basically constant. Table 2 and Fig. 3 show that the q_u of soil samples S6, S12, and S18 with 6% NM are 180.63, 163.23, and 104.44 kPa, respectively. Compared with S6, the q_u of S12 and S18 decrease by 17.4 and 76.19 kPa, respectively.

The test results show that NM can significantly improve the engineering properties of soil, especially when the water content of the sample is 16%. The increase in the strength factor for the tested soil samples reached 308.08% with soil water content of 16%, and can reach 235.71% with soil water content of 22%. This indicates that NM has a broad application in engineering practice of soft soil foundation treatment. However, the reinforcement mechanism of NM clay is unclear at present [9]. Here, we discuss the reinforcement mechanism from the following three important aspects.

The lattice structure of the surface of NM material is different from that of regular structures because of the small particle size. As the surface atomic number increases, the MgO bonds detach from the residual bond, leading to a certain chemical activity [1]. NM can change the major links between soil particles and form a new bond between the clay particles; this reduces the pore number and size between the clay particles. The large soil aggregates are combined further and close the pores between them, forming overall coupling. This improvement in the microstructure of clay soil can improve the mechanical properties and durability of the soil, but the strength of a hardened body with dense structure comes mainly from the particle bonding. The rigidity of the structure is high, indicating a rise in brittleness [2]. When $\varepsilon < 1\%$, with NM content increasing, the strength of the soil samples rises rapidly at first, then the growth rate slows down. This indicates that the initial deformation modulus and stiffness of the soil sample increases, suggesting that the damage is caused by brittle fracture. When $\varepsilon > 1\%$, as NM increases, the slope of the curve is steeper when the stress of the soil sample drops, indicating that the decrease in the stress deformation at the same magnitude is smaller.

NM is highly hydrophilic and has a large specific surface area (about 16 m^2/g). This results in high surface energy and strong adsorption activity. When preparing the specimens for testing, we found that the soil samples with added NM were thicker and harder after mixing than those without NM with the same soil water content. This is because NM can adsorb free water in the soil by adsorbing the water molecules on the surface of the NM particles. This adsorption helps increase soil strength [18].

The average particle size of NM material is 40 nm. When NM is mixed with wet soil it has a physical filling effect, reducing the amount and size of the soil intergranular pores. This increases the structural strength of the soil. After testing, we observed the NM clay section and found a large amount of white nanometer-sized magnesium powder particles in the soil. These nanometer-sized magnesium powder particles or aggregates have a filling effect that improves the pore structure of the clay and increases its strength. However, being a nanoparticle material, while the surface energy and surface tension of NM is very high, it exhibits no gelatination. When the content of NM in the soil increases, the white particles that are not involved in the reaction form stress concentration points in the clay, affecting the strength of the clay. This effect can be called the "dispersion effect" of nanometer magnesium powder [1, 2]. The dispersion effect can explain our results where the growth in strength for soil samples with 6% NM content was up to 308.08% while for those with 4% NM content it was up to 239.08%.

Conclusions

1. As a clay modification material, NM can significantly improve the engineering properties of soil: the strength of NM-modified clay increases with NM content. The maximum strengthening effect was observed when the NM content was 6%. However, increasing the soil water content of the clay sample caused a decrease in soil strength. When the soil water content of the soil sample was 16%, the increase in strength was most obvious.

2. Reinforcing clay with NM causes an increase of material stiffness and brittleness. The strengthening process has three main aspects: the cementation filling effect of NM, the surface water absorption effect of NM, and the pore filling effect of NM.

3. NM can be used as an additive in clay and has broad application prospects in engineering practice.

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