Research on properties of solidified loess with calcined ginger nuts in rammed earth for sapping area of earthen sites

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Abstract. As a non-toxic and pollution-free curing agent, calcined ginger nuts is introduced to protect rock soil cultural relics recently. In order to study the weatherability, chroma and mechanical properties of solidified loess with calcined ginger nuts, based on the reinforcement project of sapping area of Niutoucheng site in Lintan County of China, a series of tests were conducted at different ages. The results show that the properties of solidified loess are related to the dosage and curing ages. With the increase of dosage and ages, the anti disintegration and anti shrinkage properties are improved, and the mechanical properties are also improved. This study validates that as a new material, calcined ginger nuts is an effective curing agent for rammed earth to reinforce earthen sites. Moreover, the study provides support for its application in earthen sites and reveals its potential engineering practical value.

1 Introduction

Earth sites are relics left over from various activities such as production and living in human history, and they are an important cultural relic resource [1-4]. China has a long history and extremely rich earth sites resources which has outstanding historical, artistic and cultural value [5]. However, these archaic earth sites face serious diseases, such as sapping, collapse, crevices, flaky denudation and gullies, and current state is not good [6-9]. The damage mainly comes from the natural and man-made threat factors [10]. In addition, the natural destruction process is long and its speed is slow, the harm result of man-made threat is obvious but its duration is short. Both natural and human factors work together to cause serious damage to the earthen sites. Among the above diseases, the sapping problem is the most prominent.

For reinforcing sapping area, mainly technology including rammed earth and adobe masonry [11-12], which has also been applied to the protection of the site body in the large area wall foundation cut and collapse areas [13]. Comparing adobe masonry, ram not only keep better compatibility with earthen sites, but also rammed soil has strong stability and strong ability to resist wind erosion, rain erosion [14]. However, there are some shortcomings, for example, vibrations induced by rammed earth will impact the site ontology [15-19].

Recently, as curing agent, calcined ginger nuts was gradually introduced in rammed earth reinforcing earth

sites. Its main mineral composition is 70%~80% calcium carbonate and 20%~30% clay [20]. Li et al. [21] studied the curing mechanism of calcined ginger nuts and found that it mainly included hydration reaction and carbonation reaction. Li et al. [22, 23] compared chemical composition and physical property of two kind of traditional silicate materials, ginger nuts material and age, used in reinforcing ancient architecture. The study found that the modified ginger nuts could be used for repairing and reinforcing the stone, earthen, brick and ceramic relics. Zhang et al. [24] took mixture calcined ginger nuts and clay as grouting material to repair crack in earth sites, and conducted laboratory tests to reveal its physical and hydrological properties. Zhao et al. [25] studied the effect of calcination temperature of 700-1400°C on modified ginger nuts material. The research suggests that ginger nuts have a combining characteristic of hydraulicity and nonhydraulicity.

For introducing calcined ginger nuts in earth sites field, the previous studies mainly focused on its composition, curing mechanism and application as grouting material. However, as a kind of non-toxic, pollution-free material, it can also be used in sapping area reinforcement in earth sites. Therefore, as curing agent of rammed soil, its mechanical properties and weatherability were studied in this paper to provide theoretical basis for its application in reinforcement soil site.

2 Materials

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The loess near Niutoucheng site in Lintan County in China was used as rammed soil and calcined ginger nuts as curing agent. Loess and calcined ginger nuts are shown in Figure 1. The basic physical properties and parameters of the loess were tested according to the Standard of Geotechnical Test Methods (GB/T50123-2019) [26]. Figure 2 shows the particle size distribution curve of loess, and Table 1 shows its basic physical properties.



(a) Loess





Fig. 1. Rammed material



Fig. 2. Particle-size distributions curve of soil sample

liquid limit (_{@ L} / %)	plastic limit ($\omega_P / \%$)	plasticity index (I _p)	maximum dry density (g/cm ³)
28.52	12.28	16.24	1.61
optimum moisture content (%)	$\begin{array}{c} \text{coefficient} \\ \text{of uniformity} \\ (C_u) \end{array}$	$\begin{array}{c} \text{coefficient} \\ \text{of} \\ \text{curvature} \\ (C_c) \end{array}$	
14.10	4.25	1.45	

 Table 1. Basic physical properties of loess near Niutoucheng site in Lintan County

Calcined ginger nuts curing mechanism [21] mainly includes:

(a) Hydration reaction

Calcined ginger nuts contains hydraulic cementing components β -CaSiO₃ and Ca₂Al₂Si₂O₈, hydraulic components β -CaSiO₃ and Ca₂Al₂Si₂O₈ and H₂O rapid hydration reaction, β -CaO·SiO₂·nH₂O and 2CaO·Al₂O₃·SiO₂·nH₂O generation. At the same time, the nonhydraulic component CaO reacts with H₂O first to form Ca(OH)₂, so that it can be quickly cemented in the water environment to produce the initial strength. The reaction of modified ginger nuts in contact with water is as follows:

 $\beta - C aO \cdot SiO_2 + nH_2O \rightarrow \beta - C aO \cdot SiO_2 \cdot nH_2O$ $2CaO \cdot Al_2O_3 \cdot SiO_2 + nH_2O \rightarrow 2CaO \cdot Al_2O_3 \cdot SiO_2 \cdot nH_2O$ $C aO + H_2O \rightarrow C a(OH)_2$

(b) Carbonation reaction

In the later stage, the nonhydraulicity component CaO reacts with H_2O to generate $Ca(OH)_2$, and then gradually absorbs CO_2 from the soil and carbonizes to generate $CaCO_3$. The above reaction process can be described as follows:

 $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

3 Methods

Under the maximum dry density and optimum moisture content condition, quality fraction between loess and calcined ginger nuts is 0%, 4%, 8% for preparing rammed soil samples. Samples were made though static pressure method, the curing conditions are $25 \pm 2^{\circ}$ C indoor temperature and $30 \pm 2\%$ indoor relative humidity.

3.1 Disintegration test

In disintegration test, the soil samples with length*width*height (50mm * 50mm * 50mm) were used to conduct test, according to the Standard for Geotechnical Test Methods (GB/T50123-2019) [26]. The disintegration rate of the soil samples in different curing time was recorded. The age points of disintegration rate were 1 day, 7 days and 14 days. The

calculation method of disintegration amount is shown in Equation (1).

$$A_{t} = \frac{R_{t} - R_{o}}{R_{f} - R_{o}} \times 100$$
 (1)

where A_t is the disintegration rate of the sample at time point (%), R_t is the reading at the surface of the float at time point, R_o is the instantaneous stable reading of the float at the beginning of the test, and R_f is the reading of the float without sampling.

3.2 Shrinkage test

Soil samples with length*width*height (160mm * 40mm * 40mm) were used to test the shrinkage and quality loss of soil samples with different dosage at different time points. Because shrinkage and water loss of soil samples are significant in initial stage of maintenance, test node is 40 minute, 1 hour, 3 hours, 6 hours of time, and the test interval was 24 hours from the next day. The calculation formula of line shrinkage is shown in Equation (2).

$$\delta_i = \frac{z_i - z_o}{z_0} \tag{2}$$

where δ_i is the axial line shrinkage rate (%), Z_i is the length test value at test node (mm), and Z_o is initial length of sample (mm).

3.3 Chroma difference test

The chroma difference is one of the important parameters for evaluation of the protection and reinforcement of various cultural relics. This index can be used as a parameter to evaluate the influence of restoration on the appearance of the original site [27]. For earthen sites, the use of different materials or reinforcement techniques will lead to the chroma difference between the reinforcement area and the original soil area. Therefore, for the maintenance and protection of earthen sites, the chroma of the soil after reinforcement should not be different from that of the original earthen sites, and should conform to the principle of "repairing the old as the old". Therefore, it is necessary to carry out chroma difference test.



Fig. 3. Chroma test sample

Soil samples with length*width*height (160mm *

40mm * 40mm) were used to conduct chroma test on soil samples. Three measuring points were selected in each soil sample, as shown in Figure 3. Set the test time is 40 minute, 1 hour, 3 hours, 6 hours of time, and the test interval was 24 hours from the next day. The chroma difference ΔE_{ab} can be calculated according to the formula (3).

$$\Delta E_{ab} = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$$
(3)

where ΔL represents the difference between light and shade. Δa represents the color difference between red and green, and Δb represents the difference between the yellow and blue.

3.4 Unconfined compressive strength test

Strength is the most important index in the evaluation system of the reinforcement effect of ramming. Therefore, it is necessary to carry out strength test. Soil samples with diameter*height (ϕ 61.8mm*125mm) were used to test the unconfined compressive strength of soil. The test age was the same as the disintegration test. The formula for calculating the compressive strength of soil samples is shown in Equation (4).

$$q_{u} = \frac{p_{t} - p_{o}}{A}$$
(4)

where q_u is the compressive strength of the soil sample (MPa), p_t is the maximum pressure of soil samples failure (N), p_o is the pressure of the load just touching the soil samples (N), and A is the cross-sectional area of the soil samples (m²).

3.5 Shear strength test

Soil samples with diameter*height (61.8mm * 20mm) were used to conduct a rapid shear test. Shear rate is 0.8mm/min and axial pressure of 100kPa, 150kPa and 200kPa. The shear performance under different dosage (0%, 4%, 8%) was studied.

4 Results and Analysis

4.1 Water stability of solidified loess

The disintegration test results show that the final disintegration rate of the soil samples decreases with the increase of the dosage. Figure 4 shows the final state of samples disintegration under 14 days age. Soil samples of different dosage experience different processes in water, but they experience three stages early stage, middle stage and late stage. At the early stage of the test, appearance of bubbles on the surface without obvious disintegration, and the amount of disintegration is small at this stage. At the middle stage, the soil samples began to disintegrate from edges and corners, a small amount of disintegration occurs in the soil sample. In the late stage, with a large number of disintegration, the samples began to collapse. The samples with the dosage of 0% disintegrated completely, and the soil samples with the dosage of 4% collapsed into a pile of smaller particles,

but the soil sample with the content of 8% collapsed into bulk fragments.



(a) Dosage of 0%





(c) Dosage of 8%

Fig. 4. Disintegration state diagram of soil sample in later stage

The disintegration rate was calculated by Equation (1). The relationship among disintegration rate, different dosage and age of soil samples was analyzed. The analysis results are shown in Figure 5. The disintegration

rate of soil samples with high dosage and long age is less, on the contrary, the disintegration rate of soil samples with low dosage and short age is large.



Fig. 5. Trend of disintegration rate

4.2 Shrinkability

Through the shrinkage test, the shrinkage rate along the length direction was calculated by Equation (2) and the quality changes of soil samples were obtained. Figure 6 and Figure 7 show linear shrinkage rate and quality loss of soil samples varies with curing time and dosage respectively. The results show that the shrinkage trend of soil samples with different dosage is similar, and shrinkage mainly occurs in the first two days after demoulding, but the shrinkage extent is slightly different. With the decrease of moisture content of soil, the volume of soil shrinks, and the linear shrinkage rate of soil samples will change. Comparing linear shrinkage rate of soil samples, quality loss of samples under different curing ages shows a similar change trend. When the moisture content of soil sample is high, the soil sample will appear rapid water loss and dry shrinkage. When the water content decreases, the shrinkage rate of soil samples decreases.



Fig. 6. Variation of linear shrinkage of soil samples



Fig. 7. Variation of soil samples quality

4.3 Chroma difference



Fig. 8. Variation of chroma value with 4% dosage



Fig. 9. Variation of chroma value with 8% dosage

After demoulding, the chroma of the soil samples was measured, and each dosage was measured at three points each time. The difference values of ΔL , Δa and Δb of soil samples were calculated according to the test results,

and the chroma difference values ΔE_{ab} were calculated according to Formula (3). For 4% and 8% dosage soil samples, the calculation results of surface chroma after 16 days are shown in Figure 8 and Figure 9 respectively.

The results show that calcined ginger nuts dosage makes the surface color change slightly. Compared with the soil samples without calcined ginger nuts, indexes Δa and Δb of solidified soil are less change, and various trend are similar. However, ΔL change obviously, and the value of ΔE_{ab} is similar with ΔL . Therefore, the degree of light and shade of the surface color of earthen sites is the main influencing factor of chroma difference. The chroma difference values of samples with 4% and 8% dosage are basically 1.9 and 2.4, and they are all less than 3, which can satisfy the requirement of earthen sites protection [28].

4.4 Unconfined compressive strength

Unconfined compressive strength tests were carried out on soil samples, the test results are shown in Figure 10.



Fig. 10. Change of unconfined compressive strength

Figure10 shows the variation of the unconfined compressive strength of soil samples with different age and dosage. At the same age, with the increase of calcined ginger nuts dosage unconfined compressive strength increased. As increase of age, the unconfined compressive strength increases and then decreases. Because hydration reaction between the calcined ginger nuts and water dominants compressive strength in initial curing time, so the early strength is improved significantly. In the late stage, carbonation reaction is gradually obvious, nonhydraulicity component in calcined ginger nuts reacts with carbon dioxide in the air. At the same time, the reaction results heat releasing and air flow in curing stone body [29]. Therefore, the porosity of soil sample increases and the compressive strength decreases slightly in the later stage.

4.5 Shear strength

The shear strength test was carried out on the soil samples. After 14 days of curing, the relationship curve between shear stress and shear displacement under





Fig. 11. Shear stress-displacement curve of soil sample after 14 days curing

Figure 11 shows the shear stress-displacement curve of samples. As shown in the figure, compared with low dosage, the strength of samples with high dosage is higher. The shear stress-displacement curves of all samples experienced rising, falling and stable stages under different dosage. In the rising stage, the slope of shear stress-displacement curve is similar during shear stress increases to the peak value. In the falling stage, tiny crack will appear and continue to expand and gradually form a perforating flat crack, and the soil samples are cut into two parts. Therefore, the shear strength begins to decrease. In the stable stage, the shear stress drops very slowly and is relatively stable, and the soil samples have been completely destroyed at this stage.

5 Conclusions

Ramming is a very effective method to reinforce the sapping area. The use of rammed earth materials will impact the effect of ramming. Therefore, the weatherability, chroma and mechanics of the solidified soil using the calcined ginger nuts were studied in the laboratory test.

The introduction of calcined ginger nuts can improve the resistance of effectively soil to disintegration and shrinkage. The rate of soil disintegration decreases with the increase of dosage and age. The shrinkage trend of soil samples with different dosage is similar. The shrinkage rate of samples changes rapidly in the early stage, but the shrinkage degree of soil samples with different dosage is different, and compared with low dosage, the shrinkage of soil samples of high dosage is smaller. Calcined ginger nuts makes the surface color of soil samples change slightly when the dosage is lower, and the main change is the degree of light and shade.

Compared with low dosage, the strength of high dosage samples is higher. Moreover, with the increase of age, the unconfined compressive strength showed an increasing trend in the early stage and decreased in the later stage. The reason is that hydration reaction between the calcined ginger nuts and water dominants compressive strength in initial curing time. In the late stage, carbonation reaction is gradually obvious. At the same time, the reaction results heat releasing and air flow in curing stone body. Therefore, the porosity of soil sample increases and the compressive strength decreases slightly in the later stage. The shear strength of samples with high dosage is higher. The changing trend of shear stress-displacement curve of soil samples with different dosage is similar, and the curve has experienced rising, falling and stable stages during the test.

Acknowledgments

This work has been supported by the National Natural Science Foundation of China (41901079, 41971093), Independent Research Project of State Key Laboratory of Frozen Soil Engineering (SKLFSE-ZQ-50) and the Foundation for Excellent Youth Scholars of NIEER, CAS (Y9510608).

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