Study on Structural Improvement of Loess by Waxy Rice Powder in Weak Acid Environment

Xiaowu Tang¹,*, Yue Yu¹,a, Minliang Fei¹,b, Guoping Sun²,c and Wenfang Zhao¹,d

¹Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310058, China
²Researcher, Zhejiang Institute of Cultural Relics and Archaeology, Hangzhou 310014, China

*Corresponding author e-mail: tangxiaowu@zju.edu.cn, a yuyuecorey@163.com, b 874664614@qq.com, c 1784823752@qq.com, d zwfzju@163.com

Abstract. Waxy rice is widely used in many ancient buildings due to their good performance in some fields (such as caking property, impermeability, weatherability, etc.). In the humid environment of South China, the excavation of ancient sites is faced with many problems, especially for sites with deep burial depth, it is necessary to set support and minimize the impact on the site environment. In the excavation project of Jingtoushan site, located in the town of Sanqi, Yuyao, Zhejiang Province, China, the loess between the steel structures supports needs to be reinforced. Waxy rice, as a traditional Chinese building additive, was used as the reinforcement of this project. Therefore, it is of great significance to explore the best proportion of waxy rice powder mixed with loess. In this paper, the standard columns with different proportion of waxy rice powder were made, and the uniaxial compression tests were carried out after curing for 0~180 days in standard humid environment (25°C and 60% humidity). It was found that the soil columns with 2% waxy rice powder had the best improvement effect. Due to the weak acidity of groundwater in South China, loess specimens mixed with 0%, 1%, 2%, 3% waxy rice powder was soaked in acetic acid solutions of 0mol/L, 0.5mol/L, 1mol/L and 2mol/L respectively, and the consolidation fast shear test, SEM test and mercury injection test were completed. The results show that the overall structure of the specimen is improved when the concentration of acetic acid is low. Acetic acid dissolves the calcium carbonate in the loess -waxy rice structure, quickly and effectively destroys the poor pore structure in the loess, and makes the waxy rice powder filled as the binder between the soil particles, forming a new structure. The improved structure has strong shear strength. When the concentration of acetic acid is high, the cementitious substance between the soil particles dissolves and the pore content increases. The waxy rice powder is not enough to fill the extra pores. Therefore, it is suggested that the proportion of waxy rice powder should be more than 2% in the areas with strong acidity. The study provides a useful reference for the excavation and follow-up protection of earthen sites in the acid environment of South China.
1. Introduction
Jintoushan site (30°01'30''N, 121°21'36''E) is a typical shell mound lying in eastern Zhejiang province suffering from a long rainy season. Temperature and humidity of Jintoushan site is measured by remote electronic acquisition instrument and can be seen in Figure 1. The site is located in the chemical plant area of Yuyao, which is surround by several chemical plants (Figure 2a). The burial depth of the cultural remains is -6.8 ~ -11.0m under the thick marine clay layer. In order to excavate the site, steel structure support is needed around the excavation area (Figure 2b). During construction it needs a kind of economical reinforcing material which can not only meet the environmental protection but also not change the acid-base environment of the cultural relics. Zhang [1] found the toughness and impermeability of organic-inorganic lime mortars are related to the synergistic action of inorganic and organic matter between the nano calcium carbonate and the wrapped glutinous rice pulp film, which is the reason for the durability of ancient Chinese buildings. Waxy rice is one of the most important ingredients. Thus, a proper amount of waxy rice powder was added to the loess for strengthening support in the excavation of Jingtoushan site. Therefore, the main point of this article is to explore the best proportion of waxy rice powder mixed with loess.

As a common engineering soil, loess has attracted the attention of many scholars because of its unique collapsibility and other characteristics. There are differences in the plastic evolution trend of loess soil after acid-base solution pollution. Gerei [2] found that loess is suitable for the amelioration of solonetz type soils with an acid horizon. Existing research shows that the structure and mechanical properties of loess can be improved by acid solutions [3~5]. Meanwhile many scholars think that acid solution will destroy the structure of loess itself, so it will reduce the structural strength [6~8]. According to literature [9], the stress-strain characteristics and undrained shear strength of fine-grained clayey soil and silty clay decrease with the increase of pollutant concentration, and the attenuation range of fine-grained soil is more significant. After the addition of waxy rice powder, the microstructure of loess should be changed, which will be described in detail in the following article.

Figure 1. Temperature and humidity measurement of Jintoushan site (2020/04/12~2020/05/03).
2. Materials & Sample preparation
The loess soil samples are taken from Jingtoushan engineering soil (30°01'30''N, 121°21'36''E) in Yuyao. According to the relevant test procedures, the basic physical property indexes and salt content of the soil samples are determined. The results are summarized in Table 1. The mineral characteristics of soil samples were identified by Bruker D8 advanced type X-ray diffractometer, and the results are shown in Table 2 and Figure 3. The grading curve of loess particles is shown in Figure 4.

Table 1. Basic physical parameters of loess soil sample.

| Moisture content: % | Atterberg limits | Maximum dry density: g/mm$^3$ | Specific gravity | Calcium carbonate content: % | Organic content: % |
|---------------------|------------------|-------------------------------|-----------------|-----------------------------|--------------------|
| 12                  | 29.5             | 17.8                          | 1820            | 2.72                        | 9.8                | 2.3                |

Figure 3. XRD results of soil samples.
In order to ensure the uniformity of sample preparation, the soil sample shall be dried thoroughly and then crushed through 2mm sieve to achieve the effect of removing impurities. Then add water in sequence according to the optimum moisture content, mix with 0%, 1%, 2%, 3%, 4% and 5% waxy rice powder, mix and prepare them evenly, then put them into the steel mold with lubricating oil on the inner wall. After putting in a cool place for 24h, demould them with the demoulding machine to get the soil column sample. The method of layered compaction is used for sample preparation, with 3 layers in total, and the control height of each layer is around 67cm. Under the propagation of dynamic wave, the compaction process will have a compaction effect on the soil below this layer, and the actual compaction times of each layer will be adjusted by the way of trial compaction. Generally, the number of blows per layer is around 90. The size of the prepared column specimen is φ 100mm ×200mm, as shown in Figure 5f. The column samples were stored at 25℃ and 60% humidity for 7 days, 30 days, 90 days and 180 days respectively.

Then prepare the sample polluted by acetic acid solution, and cut the original loess sample with φ 61.8mm × 20mm ring cutter and number it. The acetic acid solution is diluted with 30% acetic acid solution. According to the pH value of the leaching solution of soil samples obtained from drilling in the site of Jingtoushan site and the consideration of being in the local chemical plant area, the concentration of acid solution was set as 0.5mol/L, 1mol/L and 2mol/L respectively. Place filter paper and permeable stone on the top and bottom of the sample cut by the ring cutter, and then use a wide leather band to bind the sample from the top to the bottom. Put them into solutions with acetic acid concentration of 0.5mol/L, 1mol/L and 2mol/L respectively, and the control group soaked in distilled water was added (4 samples for each group), as shown in Figure 6. After five days soaking, the sample can be regarded as completely polluted by acid solution and then placed in a cool place to dry.
The soil of the Jintoushan site is in a weak acid environment for it's located in the chemical plant area of Yuyao. Therefore, the pH value of two groundwater samples is around 6.5. Six soil samples from different soil layers of the site are taken, and the pH value of soil leaching solution fluctuates from 5.6 to 7.0. In consideration of safety and environmental protection, acetic acid was selected as the solution additive. In this paper, distilled water and 0.5mol/L, 1mol/L and 2mol/L acetic acid solutions were prepared. The soil samples were soaked in distilled water, 0.5mol/L, 1mol/L and 2mol/L acetic acid solutions for 5 days and then taken out. Then the soil leaching solution was prepared. The pH value of the solution before and after the test was measured by pH meter. The pH test values of 0.5mol/L, 1mol/L and 2mol/L acetic acid solutions are 3.00, 2.68 and 2.44 respectively, and the pH test values of the treated soil sample leaching solution are 6.32, 5.35 and 4.58 respectively, all within the acceptable range.

Figure 5. Preparation process of soil column sample. a) Drying in 105° oven for 24 hours; b) Add water in sequence according to the optimum moisture content, mix with 0%, 1%, 2%, 3%, 4% and 5% waxy rice; c) Compaction in three times with compaction hammer; d) Scrape the surface of the sample; e) Use lifting demoulding machine to get the column sample after putting in a cool place for 24h; f) The column samples were stored at 25°C and 60% humidity for 7 days, 30 days, 90 days and 180 days respectively.

Figure 6. Preparation of loess with 2% waxy rice ratio sample by distilled water and acetic acid solutions with different concentrations.
3. Experiment & Results

3.1. Uniaxial compression test
In this paper, conventional hydraulic-universal testing machine is selected (Figure 7). The test piece is installed on the lifting platform of the material testing machine for unconfined compression test. During the test, the deformation of the test piece should be increased at a constant rate, and the rate should be kept at about 1 mm/min, and the maximum pressure when the test samples are damaged should be recorded [10]. Figure 8 shows the failure state of the samples with different proportion of waxy rice during uniaxial unconfined compression test after being placed at 25°C and 60% humidity for one month. According to the test results, the relationship between axial strain and uniaxial compression stress is shown in Figure 9.

![Hydraulic-universal testing machine](image1)

**Figure 7.** Hydraulic-universal testing machine.

![Uniaxial compression test](image2)

**Figure 8.** Uniaxial compression test of loess with different waxy rice ratio (25°C and 60% humidity for 30 days).
Figure 9. Uniaxial compression test results of loess with different waxy rice ratio in 7 days, 30 days, 90 days and 180 days.

It can be seen from Fig. 9 that under uniaxial compression stress, the peak strength of loess samples with different proportion of waxy rice powder can be seen from the stress-strain curve. In the early stage of specimen deformation development, the stress-strain curve of uniaxial compression shows a steep rising stage with small deformation, and the deformation is in the elastic deformation stage, due to the size of axial compression load is not enough to cause damage to the soil structure. It can be considered that the soil element has not entered the yield state, and the plastic deformation has not developed. When the stress produced by the axial compression load has enough capacity to destroy the
loess-waxy rice structure, the comprehensive structure of the soil begins to attenuate, and the overhead skeleton structure formed by loess particles begins to change, and finally to destroy. Based on the view of plasticity theory, with the increase of axial compression load, the deformation of soil changes from elastic state to plastic yield, the sliding deformation between soil skeleton particles increases, the connection between some particles is broken, and the micro cracks between skeleton particles appear at the same time. With the development of micro cracks and the formation of connection in the soil unit, the skeleton particles are finally broken, and the shear band in the soil is produced. From the aspect of failure form, the picture shown in Fig. 6 clearly shows that when the content of waxy rice powder is less than 2%, there is only one small crack when the sample is damaged. When the content of waxy rice powder is 3%, 4% and 5%, the sample is seriously damaged and there are several large cracks through it. In general, the mechanical properties of loess samples with different content of waxy rice powder are as follows: 2% is the best in 7~180 days, 1%, 0% and 3% following while 4% and 5% are not very ideal. For the same batch of samples, the uniaxial compressive strength of 30 days is the highest when they are placed in the environment of 25°C and 60% humidity, and the peak value of stress-strain curve will slightly shift to the right as time goes on, and the data of 90 days and 180 days have little difference (Figure 10). For the 3% trial, the gap between the former 1% and 2% and the control group of 0% was greatly reduced over time.

3.2. Consolidation fast shear test
From the above uniaxial test, the data of waxy rice powder content of 4% and 5% is not very good, so only 1%, 2%, 3% and 0% control group are selected for consolidation fast shear test. In this paper, constant strain direct shear (ZJ-2) is selected. According to the standard of geotechnical test method (GB/T50123-1999), four ring cutter specimens soaked in the same acetic acid concentration solution were used for consolidated undrained shear test (CU) under different levels of vertical ballast (50kPa, 100kPa, 200kPa, 400kPa) using. The consolidation time is 24 hours, and then pull out the fixed pin for shear test. Control the shear rate to be 0.8mm/min, record the peak load, continue to shear until the shear displacement is 6 mm, stop the machine, record the failure value, end the test after unloading [10].

![Figure 11. Shear strength index of loess-waxy rice samples by acetic acid solutions with different concentrations.](image)
According to the analysis of Fig. 11 and Fig. 12, the following difference rules can be obtained: 1) after the sample is immersed in different concentrations of acetic acid solution, the cohesion decreases generally. The cohesion of the control sample (0%) decreases significantly, while 1%, 2% and 3% of the sample increases slightly then decrease after putting in 0.5mol/L, 1mol/L and 2mol/L acetic acid solution respectively; 2) After immersion in different concentrations of acetic acid solution, the friction angle of 1%, 2% and 3% samples increased slightly, which was much greater than that of the control group (0%); 3) The increase of shear strength due to the change of friction angle is much less than that of cohesion. It is better to add waxy rice powder in weak acid environment. Compared with the control group, the samples with 2% waxy rice powder content were 0.5mol/L After immersion in acetic acid solution, the consolidated shear strength (when the principal stress is 400kPa) is determined from 215.0kPa increase to 237.3kPa, the growth rate is 10.4%; 4) After immersion in 2 mol/L acetic acid solution, the shear strength of all samples decreased, but the shear strength of 3% of the samples was the largest.

3.3. Microstructure test
The microstructural characteristics mainly include soil particles, pores and cementitious materials, among which the particles and cementitious materials are mainly observed by SEM, and the pores are tested by mercury injection method. In this paper, we focus on the change of microstructure of 2% best ratio sample after immersion in different concentration of acetic acid solution.

The key steps of SEM observation are: carefully break the sample after completely air dried, select the representative fresh face slice for sample preparation, with the size of 3mm × 3mm × 1mm, plating platinum on the surface to be photographed and paste it on the photographic plate, and then use QUANTA FEG 650 scanning electron microscope (Fig. 13a) was used to photograph the microstructure of soil samples to observe the evolution of the microstructure of soil samples after immersion in acetic acid solution of various concentrations.

The main steps of mercury injection test are as follows: select the sample soaked in each acetic acid solution, wait for it to be completely air dried, and trim the near cylindrical sample with the size of 1cm in diameter and 2cm in height in the middle with the cutter. Before the test, dry the sample to be tested in a 105°C constant temperature oven for 8h, take out the sample and weigh it, put it into an expansion gauge and seal it, place it in the pressure chamber of mercury porosimeter (Fig. 13b) to complete the low and high pressure test, repeat the steps, and complete all the samples to be tested.
Figure 13. Microstructure testing devices. (a) QUANTA FEG 650 scanning electron microscope; (b) Autopore IV9510 type mercury porosimeter.

Figure 14. 5000× SEM results of the loess samples mixed 2% waxy rice in distilled water, 0.5mol/L, 1mol/L and 2mol/L acetic acid solutions.
Figure 15. Pore size distribution curves of loess samples mixed 2% waxy rice contaminated by acetic acid solutions with different concentrations.

As shown in Figure 14, after 2% of the sample is soaked in distilled water, the pore size is about 10μm, which has also been verified in Figure 15. In the microstructure of the sample, the agglomerate morphology and granular morphology coexist, and the majority of the agglomerate morphology. After immersion in 1mol/L acetic acid solution, the samples began to show narrow pores about 20μm in length, and the cement between the clots decreased. In the sample soaked in 2mol/L acetic acid solution, it is more obvious that the large clots with a diameter of more than 5μm are corroded into small particles with a diameter of less than 1μm by the acid solution, so that a similar image of cauliflower is observed on the surface. It can be seen more intuitively from Figure 15 that peak value of pore size distribution curves of 2% samples move left as acid concentration increases. According to the pore size obtained from mercury injection test, the fine pore with the pore size of 0~0.5μm is classified as the intragranular pore, and the large pore with the pore size of 0.5μm~100μm is classified as the intergranular pore. According to the test results, the intragranular pore and intergranular pore between and within the particles are increasing after immersion in acetic acid solution.

Obviously, when pH value is less than 5 (2mol/L acetic acid), the internal structure of the loess will loosen even if a certain proportion of waxy rice powder is added, but the addition of waxy rice powder will greatly alleviate the collapse of the original structure caused by the dissolution of cemented structure between the acid corrosion particles, which is also verify the results of previous consolidation shear tests.

4. Discussion
The soil column samples used in this paper are all remolded soil. The remolding process is actually the redistribution process of soil particle arrangement. During the remolding process, the structural disturbance potential of loess sample unit is effectively released. The disturbance remolding makes the arrangement of soil particles more uniform, and the large pores and vertical cracks between particles heal, thus affecting the structural change of loess.

4.1. Change mechanism of unconfined compressive strength
From Figure 9 to figure 10, it can be seen that the failure characteristics of loess samples with different waxy rice content are different: 0%, 3%, 4% and 5% are plastic failure due to strain softening; 1% and 2% are plastic failure due to strain hardening; the difference of the failure characteristics is that the addition of waxy rice powder enhances the cohesion (positive effect) between loess particles, while the seizing of water film changes the particles of primary loess minerals inter structure (negative
effect). Due to the weak connection force between the agglomerates in 0%, 3%, 4% and 5%, the agglomerates in the sample are easy to slide under the axial pressure, resulting in strain softening and eventually failure. When 1% and 2% soil samples are partially cracked under compression, the waxy rice binding action can bear the tensile stress of this part of soil, delay the development of cracks and prevent the fracture of the whole structure, make the samples crack continuously and produce strain hardening plastic damage.

4.2. Mechanism of cohesion and angle of internal friction

After adding waxy rice powder, the water film originally wrapped around the loess particles will be attracted and pulled around the waxy rice particles with finer particle size and better water absorption, and the wet waxy rice particles will become better binders to adhere the surrounding loess particles, thus changing the inter particle structure of the original loess minerals. In the weak acid environment, the intergranular cementation formed by the next generation of clay mineral particles decomposes, so that the soil structure changes significantly. At this time, the intervention of waxy rice particles can replace the original intergranular cementation, and the macroscopic performance is that the sample with waxy rice powder in 0.5mol/L and 1.0mol/L acetic acid solution has better shear strength. If the concentration of acid solution contacted by the sample is higher and the pH value is smaller, the proportion of waxy rice powder should be increased to fill the position between particles.

5. Conclusion

In this paper, a new construction method for the protection and excavation of acid soil sites in South China is proposed. The structure of loess is improved by adding different proportion of waxy rice powder. The loess waxy rice soil sample is treated with different concentration of acetic acid solution and its improvement effect is verified by laboratory test.

(1) Before acid corrosion, the uniaxial compressive strength of loess soil column with different proportion of waxy rice powder was compared. With the addition of waxy rice powder, a new stable secondary structure was formed between the skeleton particles of loess. For the samples with more than 3% waxy rice powder ratio, the cohesive force between aggregates is weak because of the change of the grain structure of the primary loess minerals by seizing the water film. Therefore, the best ratio of waxy rice powder in neutral environment is 2%.

(2) The primary structure of the soil sample treated with acetic acid solution collapses because of the dissolution of the cemented structure between grains. At this time, adding a proper amount of waxy rice powder can increase the cohesion. In addition, because the acetic acid solution corrodes the surface of loess particles, the internal friction angle will increase. When the pH value of external water environment is less than 5, 3% waxy rice powder should be used.

(3) The possibility of this research result in practical application has been proposed in this paper. The Jingtoushan site under construction urgently needs a kind of economical reinforcing material which can not only meet the environmental protection but also not change the acid-base environment of the cultural relics. Adding a proper amount of waxy rice powder to the loess can achieve this effect. In the actual project, the surrounding water environment can be detected first. If there is more acid rain, more than 2% waxy rice powder will be added in the upper part; if the pH value of groundwater is relatively low, more than 2% waxy rice powder will be added in the bottom.

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