Research Article

Study on Bottom Damp-Proof Method of Cave Dwelling

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Received 30 October 2017; Revised 27 April 2018; Accepted 16 May 2018; Published 24 June 2018

Academic Editor: Flavio Stochino

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The cave dwelling, as one of the most typical and traditional characteristic local housing styles in the loess area of Northwest China, has been adopted widely in many areas since ancient times. The construction of the cave dwellings supports environmental protection, makes use of innovative construction technology, and preserves historical cultural heritage. The cave dwellings have practical significance and play an important role in the current society. Although there are many natural advantages to use cave dwellings, they also pose many problems, such as high moisture, inadequate lighting, poor ventilation, insufficient strength, and so on. The most serious problem is related to moisture, which affects the comfort, security, and safety of the residents; it needs to be addressed. The authors propose to resolve this problem by developing a method of building a damp-proof course in the bottom of these cave dwellings. Meanwhile, specified experiments were carried out to validate the feasibility of this method. The results show that the method is reasonable and practical, and it can be implemented easily and conveniently in the future. This research has significant practical value; the results can improve people's living environment and increase comfort and safety of cave dwelling.

1. Introduction

The loess plateau of Northwest China is dry and cold in winter and hot in summer with scarce rainfall. For this reason, the region provides a good natural condition for the construction of cave dwellings, which has become an ancient and unique residence pattern on the loess plateau. The cave dwelling can be dated back to the cave-living period, which originated in ancient times. The archaeological cave sites in the Yangshao cultural period, which have been excavated in the Shaanxi Province, China, demonstrated that such cave dwelling appeared about 7000–5000 years ago. Now, there are still about 30 million people living in the caves of the loess area, which shows that cave dwelling is still widely used [1].

The cave dwelling, as a hot research topic in recent years, has been studied by many scholars. They have achieved a series of important research results. Yang, a professor of Xi'an University of Architecture and Technology, developed a thermal design of a zero energy consumption cave-dwelling solar house by studying the characteristics of a traditional cave dwelling and considering the abundant solar radiation resources in the loess plateau of northern Shaanxi Province [2]. In particular, Liu, an academican of the

Chinese Academy of Engineering, has studied in depth on the sustainable developments of the cave dwelling. His results have been unanimously recognized and highly valued among China and the world experts [3]. However, the research of cave dwelling is carried out relatively late in China. This research needs to be broadened and further investigated.

The cave dwelling is the most distinctive residence style in the loess region. Regarding the whole environment and the monomer cave dwelling, the architectural morphology of the cave dwelling are conformed to the nature and symbiotic coexistence with the ecological environment [4]. The cave dwelling shows very strong vitality because there are so many advantages on it. The building material of the cave dwelling is natural eco-friendly. The living condition is warm in winter and cool in summer. Its orientation and interior layout are reasonable and regular. The energy utilization is also very ingenious and efficient [5]. As a coin has two sides, the traditional cave dwelling also has some problems, such as high moisture, inadequate lighting, poor ventilation, insufficient strength, and so on. Among these shortages, high moisture is the most serious problem, which can affect the comfort and security of the residency. In some situation, high moisture even threatens the safety of people's

FIGURE 1: The statistical survey data of the main disadvantages of cave dwelling.

living. So, this problem must be solved [6]. It is necessary to find an effective method of cave-dwelling damp-proof measures by drawing on modern building technology. The research can help people to improve their living environment; increase their living comfort; and ensure their living, health, and safety. It has important application value and practical significance.

2. Research and Analysis

In order to further understand the living conditions of current cave dwellers, the authors carried out a survey in Yan'an city, Shaanxi Province. This questionnaire survey is mainly based on traditional cave-dwelling villages. So some typical old villages were chosen and most of the residents here live in cave dwelling for a long time. The participants' feelings of cave dwelling come from their real experience, and the reliability of the survey is high. In the questionnaire survey, 267 questionnaires were issued, and 243 were returned. Of the 243 questionnaires returned, 229 were valid. In order to ensure the effectiveness of the results, the authors selected 243 questionnaires and eliminated all questionnaires which were incorrectly completed, for example, those with unanswered questions or those with the same answer to every question. According to the statistics, 91.0% of the questionnaires were returned and 85.8% were valid. This questionnaire is a comprehensive survey of the comfort of cave dwelling, which covers a wide range. In order to ensure the rationality and representativeness of the questionnaire, a lot of field investigation and data consultation were carried out. The main aim of the questionnaire is to understand the actual feelings of the villagers on the living environment and

FIGURE 2: The statistical survey data of indoor humidity of cave dwelling.

to determine the practical significance of this study. The questions are simple and direct, and the result is clear at a glance. The two questions related to this research are shown in Figures 1 and 2.

For the question "What is the main disadvantage of cave dwelling?", the results are shown in Figure 1.

For the question "Can you describe the air humidity in cave dwelling?", the results are shown in Figure 2.

Figure 1 shows clearly that more than 40% of people expressed frustration that the caves "easily get damp" due to the lack of damp-proof measures. Figure 2 shows that 10% people choose very damp and 57% people believed that their current residential cave was a little damp or even highly humid. The living condition is uncomfortable. Inside caves, the high air humidity will not only cause damage to indoor furniture, but will also affect physical health, resulting in diseases like rheumatism, arthritis, and so on. The caves are not only uncomfortable, but they also have some safety issues [7]. Thus, for cave dwelling, the problem of high moisture has become one of the most undesirable issues. New measures and methods are required to decrease moisture, to improve damp-proof, and to reduce seepage of the cave dwellings.

Loess is the major building material for cave dwellings. Its particles are very small, containing calcium carbonate, and are rich in K, Cl, N, P, and other mineral elements. It easily deliquesces when meeting with the water. Because of the above reasons, water leakage, large deformation, and severe humid will occur when the cave dwelling suffer from heavy and long-term rainfall withstand [8]. The dry loess has better compression performance, while its tensile strength is usually very poor and easily causes brittle failure. When soaked by water, the shear strength of loess drops rapidly.

FIGURE 3: Damp-proof course at the bottom of the cave dwelling.

This feature can threaten residents' safety. The loess on sides, top, and bottom of the cave dwelling are easily prone to get damp. This phenomenon happening on the top and lateral walls of the cave are related mainly with the water of rainfall and irrigation. For low precipitation in the loess plateau, it is helpful to reduce the damp on the top and lateral walls of the cave dwelling by maintaining a good rainwater drainage system and reducing water consumption by human activity. However, due to the influence of groundwater and capillarity of loess, when water supply is adequate, it is easy to get damp. Especially, the phenomenon of getting damp is more obvious in the corners and bottom-side wall borders in cave dwelling. It tends to form white crystals due to the precipitation of salt from water. Thus, the cave dwelling damp-proof technology should be focused on the bottom of caves. The bottom of the cave dwelling is the foundation of the whole cave. For modern architecture, the damp-proof course can be directly set up in the foundation construction. In contrast, based on special material and construction methods, unlike modern architecture, it is unable for cave dwelling to set up damp-proof course directly after excavating foundation. Therefore, traditional cave dwelling are seldom carried out effective damp-proof treatment to its bottom. This also leads to serious dampness. In order to solve this problem, the authors proposed the idea of "reverse construction method" in the construction of cave dwelling. People should build the roof and wall firstly, and then construct damp-proof course on the bottom of the cave dwelling.

3. Processing Method

The authors proposed to use lime-soil as a damp-proof course at the bottom of cave dwelling. To enhance the performance of damp-proof course, moisture-proof linoleum is used in combination with lime-soil, as shown in Figure 3. Specific practices are listed as follows.

First, dig 30–50 cm down from the surface of the cave dwelling to set the lime-soil cushion. The volume ratio of lime to loess can be about 1:9, 2:8, or 3:7. The cushion should be layered and compacted. The thickness of each layer is about 30 cm before compaction, and the thickness is

FIGURE 4: The schematic diagram of the range of lime-soil damp-proof course.

about 15 cm after compaction. After the final compaction, the indoor floor is higher than the outdoor floor to prevent flooding. The outdoor cushion extends outward no less than 100 cm from the cave and no less than 50 cm on both sides of the cave dwelling. A layer of damp-proof linoleum plastic film is set at the place where the side wall and the lime-soil cushion are connected. This approach can effectively impede the flow channels of underground water, slow down the migration rate of soil moisture, and reduce moisture accumulation. The damp-proof course comprises lime-soil and linoleum, which helps to decrease dampness in the cave dwelling. The sketch drawing is shown in Figure 4.

4. Discussion on the Feasibility

In order to validate the feasibility of the proposed method of adding damp-proof cushion, the lime-soil permeability test and a cave penetration simulation test were designed and carried out. The basic physical parameters of the soil are shown in Table 1.

4.1. Lime-Soil Permeability Test. In order to investigate the effect of lime content of the lime-soil on its permeability, permeability coefficients with different lime contents were tested abiding by the variable head permeability test. This method could provide the experiment reference for improving damp-proof ability of cave dwellings. The test equipment used is the TST-55 type variable water head permeability tester, as shown in Figure 5. The variable head method refers to the SD128-012-84 (hydroelectric earth test standard). The method of preparation of samples applies JTJ051-93 (highway geotechnical test regulation).

The instrument and the schematic diagram of the variable water head permeability test are shown in Figures 5 and 6. The key points of the variable head permeability test are as follows.

Take four samples with the special cutting ring for the permeability coefficient test. The dry weight content of the lime in these four samples is 0%, 10%, 15%, and 20%, respectively. Weigh 3–4 kg representative dry soil sample which is accurate to 1 gram, and measure the dry moisture

TABLE 1: Properties of the soil samples.

Parameters	Values
Density (g/cm^3)	1.62
Moisture content (%)	8.06
Specific gravity	2.71
Void ratio	0.81
Dry density (g/cm^3)	1.50

FIGURE 5: The instrument of the variable water head permeability test.

content. Install the instrument on which the sample is loaded and check for leaks. Inject water into the permeability pipe (3), making it up to the predetermined height. After the water level is stable, open the water switch (2(1), 2(2)), make the water pass through the sample, and begin to measure the water head when the water overflows from the water outlet pipe (6). Then record the initial water head H_1 . After the time t , the final water head H_2 is recorded.

The permeability coefficient (K_t) is given in the following equation:

$$K_t = 2.3 \times \frac{FL}{at} \ln \frac{H_1}{H_2}, \quad (1)$$

where F is the cross-sectional area of sample, L is the thickness of sample, a is the cross-sectional area of the piezometric tube, t is the time from the beginning to the end of the recording process, H_1 is the initial water head, and H_2 is water head after time t .

Finally, the change curve of the permeability coefficient over the different lime contents is shown in Figure 7.

Figure 7 shows that the permeability coefficient of lime-soil decreased rapidly as the lime content increased. The lime-soil permeability coefficients were significantly smaller than that of the untreated sample. Furthermore, this showed that liming could effectively decrease the permeability of loess and reduce the degree of the damp. The trend of the curve is relatively gentle when the lime content is greater than 10%, and this mass ratio is equivalent to the 2:8 volume ratio of lime-soil, so the volume ratio of 2:8 in lime-soil is a better choice.

4.2. Cave-Dwelling Model Penetration Test. In order to further investigate the practical application of the lime-soil damp-proof course at the bottom of the cave, the cave model

FIGURE 6: Schematic diagram of the variable head permeability test. 1: permeability tester; 2: water switch; 3: piezometric pipe; 4: supply pipe; 5: gas outlet pipe; 6: water outlet pipe.

FIGURE 7: The relationship curve of permeability and lime content.

penetration test was designed and carried out. Main test steps are as follows.

Samples were prepared in a rectangular mold of 40 cm-length, 20 cm-width, and 20 cm-height in accordance with the actual size of the cave (3.6 m-cave width, 1.8 m-side wall height, 1.8 m-arch height, and 6 m-depth). Considering the actual conditions of sampling, transportation, sample preparation, and test site, the proportion of this paper is 1:30. The loess of the model is taken from Yan'an, which is the same as the field-investigated cave dwelling. Two small size caves were dug into the two sides of the model, one has lime-soil cushion and the other does not. The wetting condition based on the largest rainfall of this area in history was considered. The most unfavorable situation has been taken into account. The bottom of the model was uniformly wetted with water at an interval of eight hours. 200 ml water was added each time to ensure the bottom was evenly soaked. The model was sealed with a black plastic bag. Then, the soil moisture content was measured every 24 hours. After each measurement was completed, the model was continued to be added with water, sealed, and stood for a while.

FIGURE 8: Front elevation (a), back elevation (b), and a longitudinal cross section (c) of the cave dwelling model (unit of dimensions: mm).

FIGURE 9: Moisture content changing with time: (a) model 1 and (b) model 2.

It is shown in Figure 8. A 2:8 volume ratio lime-soil cushion was set on a half of the bottom side. At the same time, there is no lime-soil cushion on the other half of the model. At the beginning of the experiment, the initial water content measured in the interior of the cave was the same.

Two models were tested. After five days of continuous measurement, the relationship between water content and time was obtained, as is shown in Figure 9.

Figure 9 shows that after being soaked for five days, the change in trend of water content is relatively smooth. What is more, the moisture contents measured of the treated half of the bottom were lower than that of the untreated half.

Because of the dimensional effects, there is a certain difference in the test dates between the scale model test and real cave dwelling. However, the comparison relationship between different soil permeability is similar because the scale ratio is same. The scale model test mainly investigates whether there are obvious differences between the permeability of lime-soil and loess in cave dwelling and whether in the prototype or in the model, the trend that the lime-soil damp-proof layer can effectively reduce the water penetration in cave dwelling is similar. The research concerned more about the trend than precision of the test result. It can be seen that the trend of the two curves has a clear

distinction, which shows using lime-soil as damp-proof course in cave dwellings is feasible.

5. Conclusions

Aiming at reducing dampness of cave dwellings and in view of the actual situation of the loess region, the authors proposed the new processing method by which the damp-proof course was set at the bottom of the cave, as it comprised the lime-soil cushion and the linoleum. Its feasibility was discussed and studied by the lime-soil permeability test and cave model penetration test. The results of this study are as follows:

- (i) The field investigation and questionnaire survey showed that humidity has become one of the main problems of cave dwelling environment and must be solved.
- (ii) The permeability coefficient of lime-soil decreased rapidly as the lime content increased and was significantly lower than that of the untreated soil. It proved that lime-soil could effectively decrease the permeability of loess, thus reducing the degree of dampness. Considering the test result, the volume ratio of 2:8 in lime-soil is a better choice.
- (iii) The results of cave model penetration test showed that the change of water content of the treated cave was relatively insignificant. And the measured moisture contents were lower than those of the untreated cave. This showed that lime-soil could effectively be damp-proof.

In addition, the estimates show that the retrofit cost of a common cave dwelling is about 1000 RMB or 170 USD by using the lime-soil layer bottom damp-proof method. The increased cost accounts for only 1.0%–1.6% of the total cost. In comparison with the current desiccant dehumidification methods, the cost of using lime-soil layer is the same as the cost of using two years desiccant. However, there is no subsequent cost to use lime-soil, but the desiccant must be used for a long time. Obviously, using lime-soil layer as damp-proof method for cave dwelling is very convenient and economical.

In conclusion, the method is reasonable and practical, which can be implemented easily and conveniently in the future. This work also has practical values. Lime-soil cushions will improve living quality in the loess region and consequently benefit the preservation and development of cave architectures.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by Shaanxi Postdoctoral Research Funding Project (Grant no. 2017BSHEDZZ114), Natural Science Foundation Youth Project of Shaanxi Province of China (Grant no. 2015JQ5189), Natural Science Foundation

General Project of Shaanxi Province of China (Grant no. 2013JM7028), Basic Research Fund of the Central University of Chang'an University (Grant no. 310828171007), and Science and Technology Planning Project of Yulin Technology Division (214028170376).

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