Quantitative Analysis of Mold Growth Differences on Surfaces in Damp Soil Ruins Affected by Ventilation and Lighting Modes: Soil Ruin Exhibition Halls in High-humidity Regions

Yonghui Li*¹, Huarong Xie², Daisuke Ogura³, Shi Hu⁴ and Qinglin Guo⁵

¹Associate Professor, Key Laboratory of Urban and Architectural Heritage Conservation of Ministry of Education (Southeast University), School of Architecture, Southeast University, China

² Master, School of Architecture, Southeast University, China

³Associate Professor, Graduate School of Engineering, Kyoto University, Japan

⁴Lecturer, School of Architecture, Southeast University, China

⁵Researcher, Conservation Institute of Dunhuang Academy, China

Abstract

It is a challenge for the conservation of soil ruin sites that molds grow on the surface of damp soil ruins in soil ruin exhibition halls in high-humidity regions. The ventilation and lighting modes of soil ruin exhibition halls directly affect mold reproduction, but studies on the quantitative relationship between environmental factors and mold propagation on surfaces in damp soil ruins are insufficient. The Wenzhou Qiaolou soil ruin was selected as an example in this study, and rammed earth from this ruin was used as the experiment sample. For the ventilation and lighting modes as experimental variables, four ventilation and lighting environmental conditions were simulated for 56 days in a laboratory to compare differences in mold growth on samples of damp rammed earth surfaces. In this study, the difference of mold growth in different ventilation and lighting conditions were discussed, and some suggestions for the environmental management of soil ruin exhibition halls in high-humidity regions were given.

Keywords: soil ruins exhibition hall; damp soil ruins; mold growth; ventilation; lighting

1. Introduction

The southeast coast of China with an elevated groundwater table experiences high air relative humidity, particularly during the rainy season when air relative humidity is typically above 90%. Therefore, molds inevitably grow on surfaces in damp soil ruins in high-humidity regions because of the abundant moisture content of rammed earth and the significant air relative humidity level on these surfaces. Mold growth contaminates the appearance of soil ruins, and thus, damages their presentation and value.

Studies on mold growth on cultural relics, indoor settings, caves, and ancient tomb murals in damp environments are numerous¹⁾⁻⁴⁾. Research on the influence of environmental factors, such as temperature and relative humidity, on mold reproduction is also abundant. Existing studies show that the optimum temperature for

*Contact Author: Yonghui Li, Dr. Eng., Associate Professor, Key Laboratory of Urban and Architectural Heritage Conservation of Ministry of Education (Southeast University), School of Architecture, Southeast University, Si Pai-Lou 2#, Nanjing, 210096, China Tel: +86-25-83790530 Fax: +86-25-83790530 E-mail: liyonghui@seu.edu.cn (Received April 8, 2015 ; accepted November 6, 2015) DOI http://doi.org/10.3130/jaabe.15.133 mold germination is between 0 °C and 30 °C, whereas the optimum relative humidity is from 75% to 100%^{5,6)}. For damp soil ruins, many authors have focused mainly on analyzing mold categories^{7,8)}. However, studies on the quantitative relationship between environmental factors (e.g., ventilation and lighting) and mold reproduction on surfaces in damp soil ruins are insufficient. Hence, developing an environmental design for soil ruin exhibition halls as well as protecting and managing soil ruins have become challenging tasks.

The present study mainly aims to investigate different mold growth phenomena on surfaces in damp soil ruins under various ventilation and lighting conditions. The Wenzhou Qiaolou soil ruin was selected as an example in this study, and rammed earth from this ruin was used as the experiment sample. For the ventilation and lighting modes as experimental variables, four ventilation and lighting environmental conditions were simulated for 56 days, and then a mold breeding contrastive experiment was performed in a laboratory to compare differences in mold growth on samples of damp rammed earth surfaces. Mold growth area ratio (MGAR) and mold growth grade (MGG) were adopted as indicators to quantify the evaluation of mold reproduction as well as to analyze the quantitative relations between the propagation characteristics of molds and different ventilation and lighting conditions. The conclusion of this study will provide a theoretical basis and scientific guidance for long-term protection and environmental management of damp soil ruins in high-humidity regions.

Wenzhou is located on the southeast coast of China, which has a subtropical monsoon climate and an annual average maximum temperature of 32.9 °C, an annual average minimum temperature of 2.4° C, and an annual average temperature of 19.3 °C. The highest annual average relative humidity is 93%, the average minimum relative humidity is 31%, and the annual average relative humidity is 70%. The underground water level in Wenzhou City, which is a high-humidity region, is approximately 1.0–1.5 m.

2. Materials and Methods

2.1 Experimental Materials

In this experiment, the average unit weight of the rammed earth samples was 2075.3 kg/m³ and their average saturation moisture content was 0.40kg/kg. The isothermal sorption properties of the rammed earth samples were measured in a laboratory according to ASTM E96-05. The maximum average equilibrium moisture content was approximately 0.075kg/kg in 90% relative humidity. To simulate actual damp soil ruins in high-humidity areas, the initial saturation degree of the rammed earth samples were maintained at 75% to 90% (moisture content was from 0.30kg/kg to 0.35kg/kg) at the beginning of the experiment. The moisture content variation of samples A and B during the experiment are shown in Table 1. During the 56 days, the moisture content of samples was maintained at above 50% saturation, which is always suitable for mold growth. The bottom of samples in group C and D were in contact with water as shown in Fig.1., and the saturation degree of samples maintained at above 75% saturation. In addition, to ensure that all samples were similar and homogeneous and for the convenient observation of mold growth, the sizes of all samples were the same (approximately 28cm²) and the surfaces of all samples were smooth.

The following equipment was used in the experiment: 3D digital microscope (type: KEYENCE VHX-2000), high-precision electronic balance (type: Sartorius MSE324S-000DU; precision: $\pm 0.1\%$), luminance meter (type: Testo540; precision: ± 0.1 lux), anemograph (type: Testo435; precision: ± 0.01 m/s), and electronic temperature and humidity recorders (type: T&D RTR-53A; precision: ± 0.1 °C and $\pm 0.1\%$).

2.2 Experimental Method

2.2.1 Environment Control

Ventilation and lighting were the two variables employed in the experiment, and four kinds of condition (group A: ventilated and with artificial lighting, group B: ventilated and dark, group C: airtight and with artificial lighting, and group D:

Table 1. The Moisture Content Variation of Samples during the Experiment

Time (dava)	Moisture content of samples (kg/kg)			
Time (days)	Group A	Group B		
0	0.3660	0.3581		
7	0.3362	0.3338		
14	0.3177	0.3192		
21	0.3001	0.3037		
28	0.2827	0.2884		
35	0.2637	0.2707		
42	0.2455	0.2556		
49	0.2273	0.2416		
56	0.2099	0.2267		



Fig.1. Schematic Diagrams of Four Conditions in the Laboratory

airtight and with natural lighting) were simulated in a laboratory. Ventilated and airtight conditions were realized by using open trays and sealed drying vessels, respectively. Artificial and natural lighting conditions were respectively achieved by using indoor lights and placing by a windowsill where natural light could enter. The laboratory was kept closed and the temperature of the laboratory was controlled at 24 °C ±1 °C by air conditioning, and the internal airflow was about 0.01 m/s. To obtain high relative humidity, KNO3 saturated solution was prepared in sealed drying vessels, which could create 95% relative humidity at 24 °C ±1 °C. The schematic diagrams of four kinds of condition in the laboratory are shown in Fig.1.

Temperature and relative humidity during the experiment were recorded using electronic temperature and humidity recorders, respectively. Simultaneously, light intensity and wind speed during the experiment were recorded using a luminance meter and an anemograph, respectively. Table 2. shows the parameters of the four groups of experimental conditions.

2.2.2 Assessment Indicators of Mold Growth

MGAR and MGG were the assessment indicators used in this study. MGAR is the ratio of the area of molds accounting for the constant area of the entire observation through a microscope with 100× magnification, which could automatically calculate

Table 2. Four Groups of Experimental Condition Parameters

Group	Ventilation and lighting model	Temperature	Average RH of air	Luminance value	Wind speed
А	Airtight and with artificial lighting		05%	200 lux	0 m/s
В	Airtight and dark	2400 1100	9370	0 lux	0 111/ S
С	Natural ventilation and with artificial lighting	24 C ± 1 C	82%	200 lux	0.01 /
D	Natural ventilation and with natural lighting		81.5%	400–2500 lux	0.01 m/s

Table 3. Assessment Standard of MGG

Grade	Growth characteristics	
0	No mold growth	
1	The beginning of mold growth is visible under a microscope.	
2	Light mold growth (covering over 10% of the sample) is visible under a microscope.	
3	The beginning of mold growth is visible to the naked eye.	
4	Light mold growth (covering over 10% of the sample) is visible to the naked eye.	
5	Moderate mold growth (covering over 50% of the sample) is visible to the naked eye.	
6	Serious mold growth (covering over 100% of the sample) is visible to the naked eye.	
7	The beginning of algae growth is visible under a microscope.	

the marked area. The calculation formula of MGAR is shown below:

$$MGAR = \frac{S_m}{S_A} \times 100\%$$

Where, S_m is the area of molds; S_A is the area of entire observation under a 100×magnification microscope.

MGG indicates the mold growth level. These assessment indicators were developed in a previous research⁹. In the present study, the assessment standard is explained in Table 3. to modify that presented in reference⁹ according to actual experimental results.

Because of the non-uniformity of nutrient in rammed earth in this case, during the experiment period, mold growths were observed and evaluated on the selected constant position on the surface of the samples weekly using a 3D digital microscope. The boundaries of mold hyphae were hard to determine, so to reduce the error of evaluation result, the results were observed and evaluated by the same person during the whole experiment period.

3. Experiment Results and Discussion 3.1 Results

Molds were natural growth from the samples, and the measured results showed that the mold type that grew on the rammed earth surfaces under the four conditions was mainly Ascomycota including Fusarium, Humicola, Aspergillus terreus and Acremonium. Fig.2. illustrates the assessment results of the four mold groups.

The molds in group A initially exhibited a slow growth phase during the first 2 weeks, and light mold growth was visible under a microscope with $100 \times$ magnification during the 2nd week. From the 3rd week on, however, the molds entered a rapid growth phase. During the 21st day, the MGAR of group A exceeded 70%, mycelium growth was evident to the naked eye, and MGG reached grade 3. After 35 days, the molds became stationary, MGAR exceeded 95%, a small amount of mold was evident to the naked eye, and MGG remained in grade 4.

The molds on the surface of the group B sample developed slowly during the first 3 weeks, in which MGAR was approximately 20% and MGG reached grade 3 by the 21st day. Four weeks later, the molds entered a fast growth period. By the 28th day, MGAR exceeded 75%, the molds became apparent to the naked eye, and MGG increased to grade 3. Starting from the 35th day, the growth period of the molds became stable, MGAR remained at 95%, and MGG stabilized at grade 4.

The slow growth period of the group C molds was only 7 days. Starting from the 2nd week, the molds in group C went into a rapid growth period. By the 14th day, MGAR exceeded 60%, a light mold growth was visible to the naked eye, and MGG reached grade 4. After 21 days, over 50% of the molds became evident, and MGG reached grade 5. After 28 days, the molds basically covered the entire surface of the rammed earth sample, and MGG remained at grade 6.

The molds in the group D sample surface were under a slow-growth phase before the 2nd week, and MGAR was less than 10%. In the second week, the molds entered a fast growing period, and MGAR reached 80%. By the 21st day, over 50% of the molds were obvious to the naked eye, and MGG reached grade 5. From the 21st day until the 42nd day, mold growth decelerated, but some algae that were observable under a microscope emerged on the sample surface by the 35th day, and MGG reached grade 7. After 42 days, mold growth stabilized, and MGAR remained above 95%.

Because of the uncertainty of mold growth, nonuniformity of nutrient in the medium and fuzzification of the boundary of mold hyphae, unavoidable errors existed in the evaluation result. The calculation error of MGAR was less than $\pm 3\%$ at the beginning of two weeks and less than $\pm 8\%$ after two weeks. The error of MGG was less than ± 0.3 . Fig.3. shows the



Fig.2.(a) Comparison of the MGAR Values among the Four Groups



Fig.2.(b) Comparison of the MGG Values among the Four Groups



Fig.3. Comparison of the Experiment Result with the Data by Viitanen (2000)

comparison of the experiment result with the data by Viitanen $(2000)^{9}$. It shows that the MGG of group A and group B (in 95% relative humidity condition) in this experiment agreed with the data by Viitanen (2000). And the mold growth regularity and germination time of four groups agreed with the results of previous researches¹⁰.

3.2 Discussion

3.2.1 Artificial Lighting and Dark

Fig.4. shows the comparison graph of the evaluation results for the breeding of molds in groups A (airtight and with artificial lighting) and B (airtight and dark). No significant difference was found between the mold growth area ratios of the two groups at the beginning

of 2 weeks, but the MGG of group A was higher than that of group B at the 2nd week. On the 21st day of the experiment, the MGAR of group B samples exceeded 70%, the beginning of mold growth became apparent to the naked eye, and MGG was grade 3. By contrast, the MGAR of group A was only 20%, the molds were only evident under a microscope, and MGG was grade 2. For the group A sample, a small amount of molds could be observed by the naked eye, MGG reached grade 4, and MGAR was maintained at over 90% after 35 days, whereas for the group B sample, MGG reached grade 4 after 42 days, which was a week later than that of group A. In the latter period of the experiment, the MGAR values of groups A and B both exceeded 90%, and the maximum MGG values of both groups remained at grade 4.



Fig.4.(a) Comparison of the MGAR Values of Groups A and B



Fig.4.(b) Comparison of the MGG Values of Groups A and B

The result showed that in a non-ventilated environment, molds emerged under both artificial lighting and dark conditions, but mold growth under the dark condition lagged behind that under the artificial lighting condition. The slow growth period for the molds under the dark condition was 3 weeks compared with only 2 weeks for the molds under the artificial lighting condition. Mold spores germination is more easily accelerated in artificial lighting than in dark conditions.

3.2.2 Different Ventilation Conditions

The comparison of the MGAR and MGG values of groups A (airtight and with artificial lighting) and C (ventilated and with artificial lighting) is shown in Fig.5. During the 1st week of the experiment, the MGAR values of groups A and C exhibited no remarkable difference, but a larger difference was found in their MGG. The molds on the surface of group A samples were invisible to the naked eye, whereas those of group C could be observed by the naked eye. The MGG of group C was two grades higher than that of group A during the 1st week. Simultaneously, the molds of the rammed earth surface in group C entered a rapid growth phase. By the 14th day, the MGAR of group C exceeded 60%, light mold growth on the surface of the rammed earth sample was evident to the naked eye, and MGG reached grade 4. By contrast, the MGAR of group A was 1/3 that of group C, and its MGG was only grade 2. In the latter part of the experiment, although the MGAR values of the two groups both stabilized at 95%, the MGG of group A remained at grade 4, whereas that of group C eventually stabilized at grade 6.

The experimental results demonstrated that ventilation significantly affected mold growth on damp soil ruin surfaces. The mold growth on the surface of the damp rammed earth under the non-ventilated condition lagged behind that under the ventilated condition. The molds under the ventilated condition entered a rapid growth phase a week earlier than that under the non-ventilated condition. In addition, the ability of molds to reproduce on damp rammed earth under the ventilated condition was significantly better than that under the nonventilated condition, as indicated by the MGG under the ventilated condition reaching grade 6, whereas that under the non-ventilated condition only reached grade 4.

The airflow on damp soil ruin surfaces contributes to disperse mold spores and subsidence, and the redeposited fungal spores will germinate and generate a colony. Additionally, a certain amount of wind speed on damp soil ruin surfaces also enhances the convective heat and mass transfer rate between the medium and air, which will accelerate mold growth.

3.2.3 Artificial and Natural Lighting

Fig.6. illustrates the differences in mold growth on the surfaces of the rammed earth samples in groups C (ventilated and with artificial lighting) and D (ventilated and with natural lighting). In the 1st week, a noticeable difference was observed in the MGG values of the two groups, a light mold growth was visible to the naked eye on the surface of the group C samples, and the MGG of this group reached grade 3. By contrast, the mold growth on the surface of the group D samples was only evident under a microscope, and the MGG of the group was only grade 1. However, the MGAR values of the two groups were nearly similar. During the 2nd week, the molds in both groups propagated rapidly. By the 21st day, the MGAR values of groups C and D were over 90% and 80%, respectively, and the MGG values of both groups were grade 5. After 28 days, the mold growth on the rammed earth samples in group C entered a stationary phase, its MGAR stabilized at over 95%, and its MGG remained at grade



Fig.5.(a) Comparison of the MGAR Values of Groups A and C



Fig.5.(b) Comparison of the MGG Values of Groups A and C



Fig.6.(a) Comparison of the MGAR Values of Groups C and D



Fig.6.(b) Comparison of the MGG Values of Groups C and D

6. However, the molds on the rammed earth surface of the group D samples continued to increase. By the 35th day, the surface of the group D samples exhibited algae growth, and the MGG of the group increased to the

highest grade (i.e., grade 7). Finally, the molds entered a stable phase.

The results showed significant differences in mold reproduction capability on the damp rammed earth surfaces between the artificially lit and naturally lit conditions. The mold growth on the damp rammed earth surface under the naturally lit condition lagged behind that under the artificially lit condition. However, under the naturally lit condition, the moist rammed earth surface exhibited algae growth by the latter period of the experiment. Although the MGAR values of the two groups were nearly similar, spore germination is rapidly accelerated in naturally lit conditions, because of the photosynthesis and the higher temperature on the damp rammed earth surfaces.

4. Conclusions

The following conclusions were drawn based on the preceding discussion.

The surfaces of all damp rammed earth samples exhibited different levels of mold growth under four kinds of ambient conditions. Mold growth under the dark condition lagged behind that under the artificially and naturally lit conditions. Moreover, mold growth on the surfaces of the moist rammed earth samples under the airtight condition lagged behind that under the ventilated condition.

For high-humidity areas, the ventilated and lit environment was conducive to mold reproduction on the surface of damp rammed earth. In particular, algae growth appeared in the naturally lit environment, which is disadvantageous to soil ruins. By contrast, mold propagation was weakest under the airtight and dark condition, followed by the airtight and artificially lit condition.

Natural ventilation and natural lighting strategies should be used cautiously in the architectural design of damp soil ruin exhibition halls in high-humidity regions. During the daily operation and management of soil ruin exhibition halls, uncontrollable environmental periods should be regulated within 1 to 2 weeks because mold will enter a rapid growth phase after this period under adverse environmental conditions.

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