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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

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Abstract

It is a challenge for conservation of soil ruins sites that molds grow on the surface in damp soil ruins in soil ruin exhibition halls in high-humidity regions. The ventilation and lighting modes of soil ruin exhibition halls directly affect the mold reproduction, but studies on the quantitative relationship between environmental factors and mold propagation on surface in damp soil ruins are insufficient. The Wenzhou Qiaolou soil ruin was selected as an example in this study, and rammed earth in this soil ruin is used as experiment samples. 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 mould 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 suggests for the environmental management of soil ruin exhibition halls in high-humidity regions were given.

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Keywords: Soil ruin exhibition hall; Damp soil ruins; Mold growth; Ventilation; Lighting

1. Introduction

The southeast coastlands of China with an elevated groundwater table experience 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.

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Studies on mold growth on cultural relics, indoor settings, caves, and ancient tomb murals in damp environments are numerous [1–4]. 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 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 in this soil ruin is used as experiment samples. 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 theoretical basis and scientific guidance for long-term protection and environmental management of damp soil ruins in high-humidity regions.

Wenzhou is located in the southeast coastland of China, which has a subtropical monsoon climate and an annual maximum temperature of 39.4 °C, an annual minimum temperature of -0.7 °C, and an annual average temperature of 19.3 °C. The highest annual relative humidity is 98%, the minimum relative humidity is 31%, and the annual average relative humidity is more than 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 0.35 kg/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 0.075 kg/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 60% to 70% (moisture content was from 0.21 kg/kg to 0.245 kg/kg) at the beginning of the experiment. 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 28 cm^2, the diameter is about 6cm) and the surfaces of all samples were smooth.

The following equipment were used in the experiment: 3D digital microscope (type: KEYENCE VHX-2000), high-precision electronic balance (type: Sartorius MSE324S-000DU; precision: ±0.0001g), luminance meter (type: Testo540; precision: ±0.1 lux), anemograph (type: Testo435; precision: ±0.01m/s), and electronic temperature and humidity recorders (type: T&D RTR-53A; precision: ±0.1 °C and ±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 conditions (group A: ventilated and with artificial lighting, group B: ventilated and dark, group C: airtight and with artificial lighting, and group D: 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. To obtain high relative humidity, KNO_3 saturated solution was prepared in sealed drying vessels, which could create 95% relative humidity at 23–25 °C.

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. During the experiment period, mold growths were observed and evaluated weekly using a 3D digital microscope. Table 1 shows the parameters of the four groups of experimental conditions.

Table 1: Four groups of experimental condition parameters.

Group	Ventilation and lighting model	Temperature	Relative humidity	Luminance value	Wind speed
A	Airtight and with artificial lighting	23–25 °C	95%	200 lux	0
B	Airtight and dark			0	
C	Natural ventilation and with artificial lighting		76%	200 lux	0.01 m/s
D	Natural ventilation and with natural lighting		70%	400–2500 lux	

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 accounted for the area of the entire observation through a microscope with 50× magnification. MGG indicates the mold growth level. These assessment indicators were developed in a previous research [1]. In the present study, the assessment standard is explained in Table 2 to modify that presented in reference [1] according to actual experimental results.

Table 2: 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.

3. Experiment results and discussion

3.1. Results

The measured result of the mold type that grew on the rammed earth surfaces showed that Ascomycota grew under the four conditions. Figure 1 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 50× 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 molds 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%.

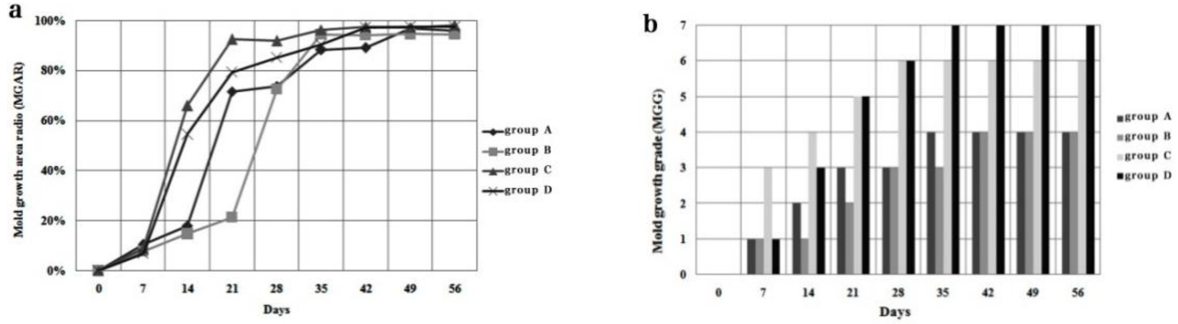

Fig. 1: Comparison of the (a) MGAR and (b) MGG values among the four groups.

3.2. Discussion

3.2.1. Artificial lighting and dark

Figure 2 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.

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.

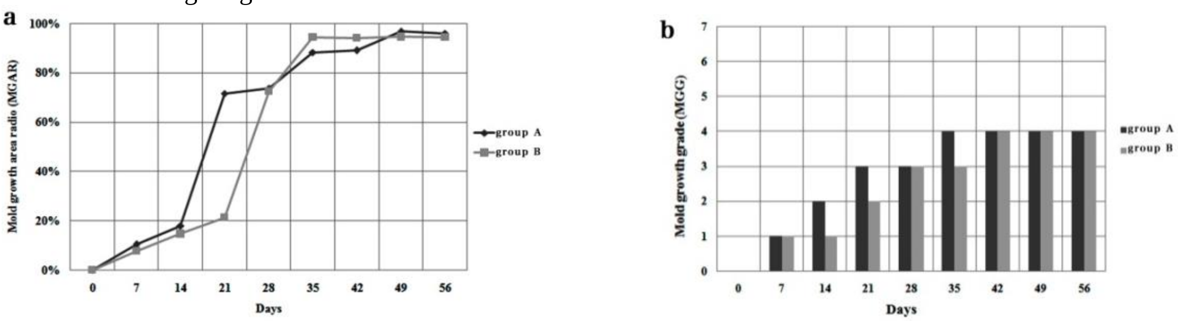

Fig. 2: Comparison of the (a) MGAR and (b) MGG values of groups A and B.

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 Figure 3. 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 non-ventilated condition, as indicated by the MGG under the ventilated condition reaching grade 6, whereas that under the non-ventilated condition only reached grade 4.

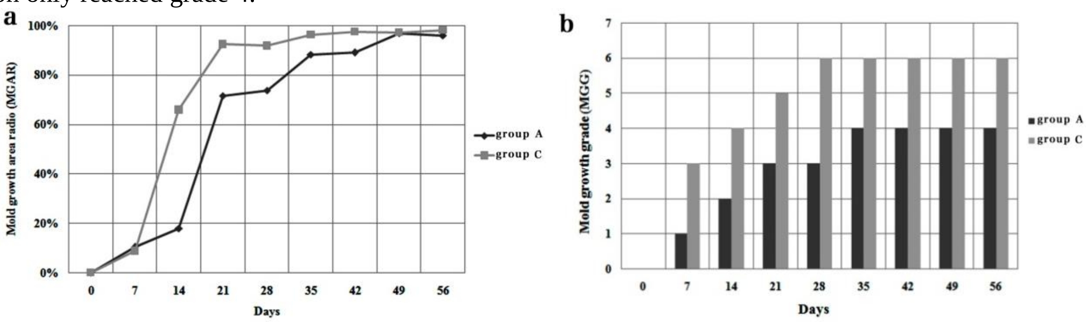

Fig. 3: Comparison of the (a) MGAR and (b) MGG values of groups A and C.

3.2.3. Artificial and natural lighting

Figure 4 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). On 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 6. However, the molds on the rammed earth surface of the group D samples continued increasing. 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 lighted and naturally lighted conditions. The mold growth on the damp rammed earth surface under the naturally lighted condition lagged behind that under the artificially lighted condition. However, under the naturally lighted condition, the moist rammed earth surface exhibited algae growth by the latter period of the experiment.

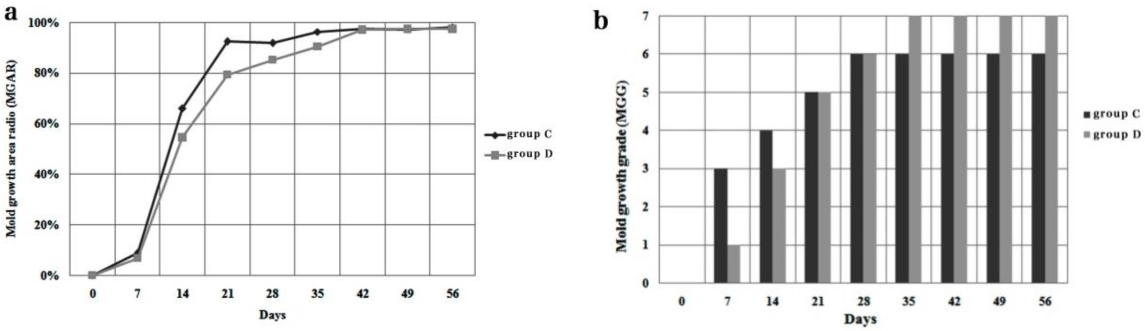

Fig. 4: Comparison of the (a) MGAR and (b) MGG values of groups C and D.

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 lighted 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 lighted environment was conducive to mold reproduction on the surface of damp rammed earth. In particular, algae growth appeared in the naturally lighted 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 lighted 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 week to 2 weeks because mold will enter a rapid growth phase after this period under adverse environmental conditions.

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