Study on the Unsteady Thermal Insulation Performance of Subtropical Oyster Shell Wall Constructions

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Abstract. There have not been many previous studies on the thermal parameters of oyster shell walls, especially when it comes to the calculation and analysis of unsteady heat transfer. In this study, the thermal parameters of oyster shells were first determined using a Hot Disk experiment. Secondly, a single-room calculation model of the enclosure's structure was established. Using a methodology based on unsteady convolution calculation combined with a Maple mathematical software model, a proposal was made to analyze the indoor temperature response of the enclosure structure under thermal excitation caused by external disturbance. This method was used to develop indoor temperature response images of five different structures, including oyster shell walls, and to rank their respective thermal insulation performances. The results of the analysis show that the structure of the oyster shell wall enclosure displayed excellent thermal insulation performance. It was found to have a similar performance to the 30 mm thick EPS board thermal insulation structure. Third, BECS energy consumption software was used to simulate the outdoor thermal excitation response under five different enclosures to obtain the respective insulation performances of each structure. Finally, the oyster shell walls have demonstrated an overall high thermal insulation performance.

Keywords: Ecological Architecture, Oyster Shell Wall, Convolution Calculation, BECS.

1 Introduction

The energy consumption of China's built structures is enormous. In 2018, the total energy consumption of the whole building process accounted for about 46.5% of total national energy consumption [1]. With the continuing process of urbanization in China, the total energy consumption for the construction and maintenance of buildings continues to rise [2]. At the same time, the spatial distribution of energy consumption by buildings is extremely uneven. In addition, the spatial distribution of carbon emissions and building energy consumption reveals a southward shift[3]as the proportion

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of energy consumption in southern China continues to increase. One of the most prominent issues is heat loss through walls, reaching as high as 30% [4]. The question of how to conserve energy in built structures in the subtropical regions of southern China is of great significance to China's future conservation practices, emission reductions, and the realization of the “dual carbon targets”.

The structure of a natural oyster shell has three primary layers, which are the cuticle, prismatic layer, and nacre layer. The surface of the oyster shell is arc shaped. When it is stacked, the internal cavity can form an air space, which provides efficient thermal insulation. Therefore, an oyster shell wall building can be "warm in winter and cool in summer," effectively reducing building temperatures and overall energy consumption.

At present, research on oyster shells mainly focuses on adding oyster shells as a modifier to existing building materials. For example, Mikami and Okumula [5] added oyster shell powder to compacted sand piles (SCP), to strengthen the soft soil seabed foundation under breakwaters and piers. Setyowati et al. [6] found that oyster shells and green materials made of polymers displayed positive structural, acoustic, and aesthetic properties, while the polymer mortar was able to reduce weight by 20%. Chen et al. [7] found that reinforcement by a modified oyster shell lime mortar can significantly improve the shear strength of low-strength mortar brick masonry walls. Research on the thermal performance of oyster shell walls has mainly been qualitative and experimental. Liang [8] studied the history of oyster shell walls and found that oyster shell walls have been used in the Lingnan area for nearly 1500 years. Liu [9], by examining the oyster shell architecture of Luyitang, first proposed the thermal insulation mechanism of oyster shell walls. Zhang [10], starting from Mark Entorp's landscape culture philosophy, emphasized that the oyster shell wall is an architectural form closely related to regional culture. Zhang [11] took the oyster shell wall architecture in Daling Village as a starting point and explored the relationship between the oyster shell wall as vernacular construction and the historical changes at the settlement. Liu et al. [12] used a double-sided heat flow meter method to measure the on-site thermal parameters of an oyster shell wall building in Shawan Town, Guangzhou City – the Renrang Public Office. The measured results showed that the delay and attenuation effects of the peak outdoor temperature were significant. Xu [13] conducted a measured analysis of heat and moisture transfer in oyster shell-walled buildings. The study found that under actual working conditions, oyster shell walls display unsteady heat transfer. Therefore, the question of how to accurately describe the heat transfer process of oyster shell walls using unsteady calculation methods has become the focus of studying the thermal insulation characteristics of oyster shell walls. Paraschiv et al. [14] proposed a one-dimensional heat transfer analysis method for homogeneous walls and composite walls. They [14] used software to perform heat transfer calculations for composite walls with up to seven layers. Tran et al. [15] proposed a new ENMIM-integrated artificial intelligence model that can estimate the energy consumption of buildings using real-world data. Danielski and Froling [16] used thermal imaging to measure in situ the thermal performance of building constructions under unsteady-state heat flow conditions. Kurtbas and Durmus [17] presented a numerical solution to the problem of unsteady three-dimensional heat transfer equations for passively heated rooms that were used to describe winter structures in the Elazig region of Turkey.

A comparative study of steady-state heat transfer and unsteady-state heat transfer shows that an unsteady-state heat transfer method can more accurately reflect the heat transfer process of an envelope structure [18]. Previous research on oyster shell walls did not include many calculations or analyses of thermal parameters, especially when considering unsteady heat transfer.

2 Research purpose and methods

Using the well-established Transient Plane Source Method, this paper measures the basic thermal parameters of oyster shells. It establishes a single-room calculation model and configures five different enclosure structures, including oyster shell walls. The indoor temperature response of each structure under thermal excitation was recorded. Then, the thermal insulation performance of each of the five non-transparent enclosure structures was ranked and cross-validated using BECS energy consumption simulation software. The aim is to provide a theoretical basis for the energy-saving design of oyster shell walls.

An overview of the research method is as follows. First, a group of oyster shell specimens of different sizes were collected. Next, thermal parameters such as thermal conductivity and specific heat levels were measured using Hot Disk. A convolution calculation was used to describe the unsteady heat transfer process of the oyster shell wall structure. Maple software was then used to draw the thermal excitation response images for sorting. Finally, building energy consumption software was used to simulate the indoor thermal environment.

3 Experiments

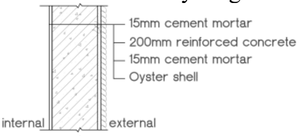
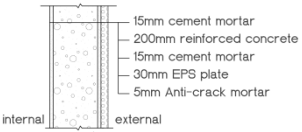
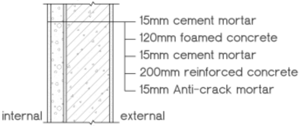
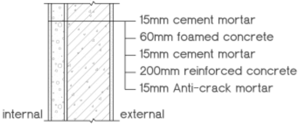
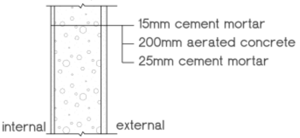
Oyster shell specimens with relatively flat surfaces were selected and separated into three different size categories (large, medium, and small). They were used to make 9 groups of oyster shell specimens. The thermal constant analyzer (model TPS1500) developed by the Sweden Hot Disk Company was used for testing. The results showed that the thermal conductivity, thermal diffusivity, specific heat, average deviation, detection depth, and average probe resistance of the oyster shell specimen group were respectively 0.400 W/(m·k), 0.177 mm^2/s, 2.262 $MJ/(m^3 \cdot k)$, 0.0019 K, 4.123 mm, and 3.828 Ω. The average detection depth was calculated to be 4.139 mm, less than the distance from the nearest boundary of the oyster shell sample to the probe. This satisfies the assumption of an infinite flat plate principally used in transient flat heat source measurement.

4 Unsteady heat transfer analysis of oyster shell enclosure structure

4.1 Establishment of a single-room model

A single-room model of the enclosure structure was constructed in the subtropical city of Guangzhou. The overall frame of the room is three meters in length, width, and height. The outer walls are equipped with five distinct types of thermal insulation, including oyster shell walls (Table 1). The floors are heat-insulated and shaded. The environment is designed to be exposed to sunlight only in the south. The floor and walls are made of non-transparent materials.

Table 1. Thermal insulation performance parameters of different enclosure structures.

Style	Construction composition	Structural hierarchy diagram
Construction a	Reinforced concrete of 200 mm thick + oyster shell	
Construction b	Reinforced concrete of 200 mm thick + EPS bord of 30 mm thick	
Construction c1	Reinforced concrete of 200 mm thick + foamed concrete of 120mm thick	
Construction c2	Reinforced concrete of 200mm thick + foamed concrete of 60 mm thick	
Construction d	Aerated concrete of 200 mm thick + plaster on both the inside and the outside	

4.2 Establishment of a single-room model

Heat transfer from heat excitation caused by external disturbance passing through the enclosure structure causes the temperature of the single room to change. In an unsteady state, the enclosure structure and the indoor air will store heat when subjected to heat excitation. In a short period of time, the indoor temperature rises. The heat balance equation of the oyster shell wall heat transfer system can be written as follows:

$$C_T \frac{\Delta\theta_R(t)}{\Delta t} + KS_T[\theta_R(t) - \theta_0(t)] - K_1S_1\delta\theta_W(t) = 0 \tag{1}$$

The full response of the oyster shell wall system to thermal excitation at radiation equivalent temperatures. When the outdoor radiation equivalent temperature is the unit step heat signal $\varepsilon_r(t)$, the single-room heat balance equation of the oyster shell wall enclosure structure can be written as ($\theta_0(t) = 0$):

$$C_T \frac{d\theta_R(t)}{dt} + KS_T\theta_R(t) - K_1S_1 = 0 \tag{2}$$

Substituting the initial conditions, the indoor temperature response function of the radiation equivalent temperature thermal excitation unit pulse signal can be obtained using:

$$\varphi_{\delta\theta_W}(t) = \frac{d\phi_{\delta\theta_W}(t)}{dt} = \frac{K_1S_1}{C_T} e^{\frac{-KS_T}{C_T}t} \tag{3}$$

Since the zero input response of the oyster shell wall heat transfer system is $\theta_R(t) = 0$, the total response of the thermal excitation from external disturbance of the oyster shell wall heat transfer system is equivalent to the zero state response of the system. Thus, the convolution integral of the impulse response function and the outdoor radiation equivalent temperature is:

$$\theta_R(t) = \int_0^t \delta\theta_W(\tau) \cdot \varphi_{\delta\theta_W}(t-\tau)\,d\tau \tag{4}$$

The full response of oyster shell wall system to thermal excitation at outdoor air temperature. When the outdoor air temperature is the unit step heat signal $\varepsilon_0(t)$, the single-room heat balance equation of the oyster shell wall enclosure structure can be written as ($\theta_0(t) = 0$):

$$C_T \frac{d\theta_R(t)}{dt} + KS_T\theta_R(t) - KS_T = 0 \tag{5}$$

Substituting the initial conditions, the indoor temperature response function of the outdoor air temperature thermal excitation unit pulse signal can be obtained using:

$$\varphi_{\theta_0}(t) = \frac{d\phi_{\delta\theta_W}(t)}{dt} = \frac{KS_T}{C_T} e^{\frac{-KS_T}{C_T}t} \tag{6}$$

Since the zero input response of the oyster shell wall heat transfer system is $\theta_R(t) = 0$, the total response of the external disturbance thermal excitation of the oyster shell wall heat transfer system is equivalent to the zero state response of the system. Hence, the convolution integral of the impulse response function and the outdoor air temperature is:

$$\theta_R(t)=\int_0^t \theta_0(\tau)\cdot\varphi_{\theta_0}(t-\tau)\,d\tau \tag{7}$$

The total response of the system under the combined action of two thermal excitations from external disturbance. The system room temperature of the oyster shell wall enclosure structure is $\theta_R(t)=\theta_{R\delta\theta_w}(t)+\theta_{Ro}(t)$, which is also true for the room temperature analysis processes of the other four enclosure structures. Therefore, the indoor temperature total response can be obtained by drawing the full response of the outdoor temperature and the full response of the radiation equivalent temperature of the five different structures using Maple software. The response function image (Fig.1) indicates that the order of thermal insulation performance is: construction b> construction a> construction c1> construction c2> construction d.

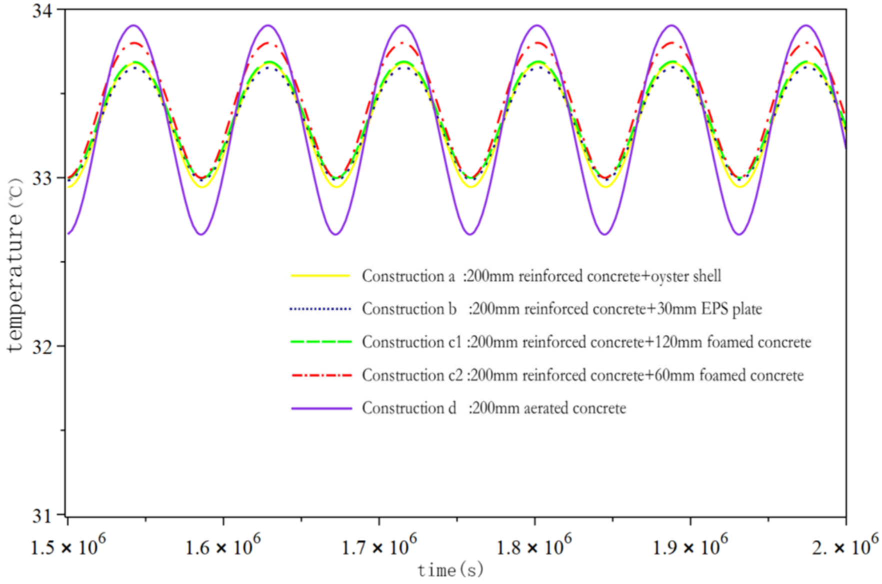


Fig. 1. The full response of five different structures under the action of outdoor air temperature and radiation equivalent temperature.

5 Simulation and experimental verification

To establish a BECS single-room heat transfer system model consistent with the calculation model, the material and thermal parameters of the oyster shell wall were set. The outdoor thermal excitation was input. The system response under the external disturbance thermal excitation was then simulated and calculated. The meteorological data comes from Guangzhou City, Guangdong Province. The southward hourly temperature of different enclosure structures was obtained. The thermal insulation performance ranking is consistent with the unsteady convolution calculation (Fig. 2).

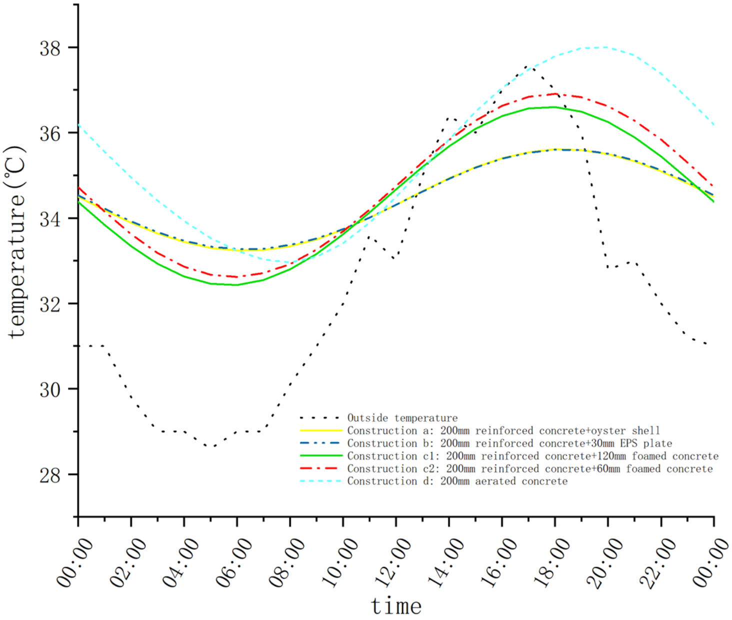


Fig. 2. Hourly comparison of outdoor temperature and southward temperature of each enclosure structure.

6 Conclusion

1) Hot Disk technology was used to measure the thermal parameters of the oyster shell. The measurement results show that the average thermal conductivity of the surface oyster shell is 0.400 W/(m·k). The average specific heat is 2.262 MJ/(m^3·k). The average thermal conductivity value is slightly greater than 0.200W/(m·k). This indicates that the surface oyster shell demonstrates a good thermal insulation performance.

2) Unsteady convolution was used to calculate the indoor thermal excitation response of five enclosure structures, including the oyster shell wall structure. The results show that the oyster shell wall structure displays good thermal insulation performance, and its performance is close to that of the 30 mm thick EPS board exterior. While the thermal insulation structure of the oyster shell wall is similar to other structures, it proved superior to the two foamed concrete internal thermal insulation structures and the self-insulation structure of aerated concrete. The BECS energy consumption software simulation result table verifies that the above unsteady convolution calculation results are more in line with the actual working conditions.

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References

1. China Building Energy Consumption Research Report 2020. Building Energy Conserva tion (Chinese and English) 49(02),1-6 (2021).
2. Wang Lining, Dai Jiaquan.: Research and judgment on China's long-term energy development trend. International Petroleum Economics 25(8), 58-63 (2017).
3. Gao Jie, Zhang Xiaoming, Wang Jianwei, et al.: Evolution and Comparative Analysis of China's Carbon Emissions and Transportation Carbon Emissions. Ecological Economy (8), 36-40 (2013).
4. Yang Jianming.: Research on Dynamic Thermal Insulation Characteristics and Thermal Resistance and Thermal Capacity Optimization of Building Walls. Guangzhou University (2020)
5. Mikami K, Okumura T.: Underwater soil improvement for port facilities by compaction piles of oyster shell-sand mixture. Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, 66-75 (2007).
6. Setyowati E, Purwanto, Hardiman G, et al.: Structural, acoustic, and aesthetic performances of double layer wall made of oyster shell and polymer as green material in green construction. AIP Conference Proceedings 1977(1), 040033 (2018).
7. Chen Z, Tang Y, Mai C, et al.: Experimental study on the shear performance of brick masonry strengthened with modified oyster shell ash mortar. Case Studies in Construction Materials, 13: e00469 (2020).
8. Liang Jiajie.: The Use of Oyster Shells and the Historical Changes of Oyster Shell Walls in Lingnan Area. Journal of Huizhou University 38(5), 41-46 (2018).
9. Liu Yixuan.: Analysis of the Scientific Mechanism of the Wannian Oyster Wall. Chinese and Foreign Architecture (02), 129-130 (2017).
10. Zhang Qin.: The Inheritance and Application of "Oyster Shell Wall" Regional Cultural Symbol in Modern Regional Cultural Landscape. Housing and Real Estate (3X), 85-85 (2017).
11. Zhang Zhenhua.: Textual research on the changes of settlement historical environment caused by local construction--Taking the "Oyster Shell Wall" in Daling Village as an example. Journal of Guangdong Vocational and Technical College of Water Conservancy and Electric Power 11(2), 29-33 (2013).
12. Liu Xikang, Zhang Lei, Meng Qinglin, et al.: Field test research on heat transfer coefficient of oyster shell wall. Building Energy Conservation (12), 31-33 (2012).
13. Xu Min.: Research on thermal and humidity characteristics of Lingnan traditional oyster shell walls. Guangzhou University (2021).
14. Paraschiv L S, Acomi N, Serban A, et al.: A web application for analysis of heat transfer through building walls and calculation of optimal insulation thickness. Energy Reports 6, 343-353 (2020).

15. Tran D H, Luong D L, Chou J S.: Nature-inspired metaheuristic ensemble model for forecasting energy consumption in residential buildings. Energy 191, 116552 (2020).
16. Danielski I, Fröling M.: In situ measurements of thermal properties of building fabrics using thermography under non-steady state heat flow conditions. Infrastructures 3(3), 20 (2018).
17. Kurtbas I, Durmuş A.: Efficiency and exergy analysis of a new solar air heater. Renewable Energy 29(9), 1489-1501 (2004).
18. He Quan, Sheng Angang, Liu Dalong.: A study on the applicability of unsteady-state calculation methods in thermal insulation design of building envelope. Journal of Xi'an University of Architecture and Technology (Natural Science Edition) 53(04), 561-567 (2021).