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The deformation of the Rock wool board external thermal insulation system based on coupled temperature and relative humidity

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Abstract. A coupled heat and humidity transfer model of external thermal insulation wall is established. The effects of different climatic conditions (winter and summer) on the deformation of the rock wool board external insulation system were simulated and analyzed by the meteorological database from Shanghai. The results show that the changes of strain and stress are fluctuated because of the variation of temperature and relative humidity, and their extremum values appear with the extreme value of temperature and relative humidity difference. The coating mortar has the highest stress and strain, and the rock wool board has the lowest stress and strain. The maximum stress can reach 1.97×10^{-3} MPa and the maximum strain can reach 1.36×10^{-4} of the rock wool thermal insulation system during the periodic changes in temperature and relative humidity within 72 hours in winter and summer.

1. Introduction

In various implementations of building energy efficiency, building external thermal insulation systems are the most common and important energy-saving structures. The cracking, emptying and even peeling of the external thermal insulation system under the action of heat and humidity is a serious problem. Due to various reasons such as climate, construction and structural design, moisture will inevitably enter the interior of the external thermal insulation system[1]. During the actual use, the heat and humidity migration and the increase of moisture content in the system are likely to produce adverse effects. The system can neither meet the requirements of energy-saving design nor maintain stability. The durability of the external thermal insulation system is closely related to its heat and humidity condition. Too high humidity will significantly reduce the mechanical strength of the insulation material and the finishing layer. Changes in temperature and humidity can cause expansion or contraction of materials. When the stress caused by temperature and humidity is large enough, the external thermal insulation system will generate cracks.



Relevant research institutions and scholars have carried out certain theoretical and experimental research on the degradation mechanism of the external thermal insulation systems. Aynur[2] analyzed the determination of four different insulated exterior walls and the optimum thickness. Pekdogan[3] researched different exterior wall structures thermal performance and the laws in three orientation. Kub Edward G [4] obtained the influence of wall cracking on the durability of the insulation system. Willimams analyzed the effect of the joint motion of the insulation layer on the bond strength of the system. Mahaboon Pachai [5] [6] carried out the degradation of concrete wall and outer mortar under different temperature loads in external thermal insulation system, and studied its bonding performance by using finite element technology and fracture mechanics theory. Nilica [7] analyzed the mechanical properties of various structural layers of external thermal insulation systems. Most of the research stays in the influence of single factor of temperature or humidity on the deformation of the external thermal insulation system, but there are few studies under the condition of coupled temperature and humidity. In this paper, the coupled temperature and humidity transfer process inside the insulation wall in the hot summer and cold winter area (Shanghai) is simulated by COMSOL Multiphysics, and the deformation of rock wool board is researched in winter and summer.

2. Numerical Simulation

2.1 Geometric model

The test wall is a rock wool external thermal insulation wall, which is composed of cement concrete wall (240mm), bonding mortar (10mm), rock wool insulation board (50mm), coating mortar (5mm) from inside to outside.

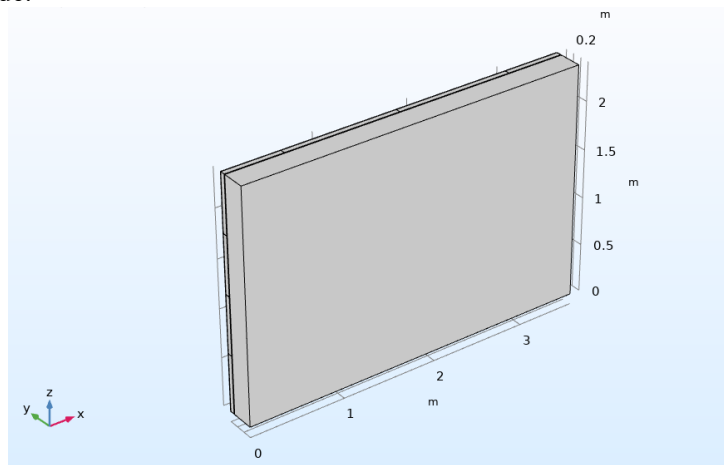


Figure 1. Geometric model of the thermal insulation system.

2.2 Control equations

2.2.1 coupled temperature and humidity control equations.

In 1959, Glaser first proposed a model that a steam flow through the wall, which laid a theoretical foundation for the heat and humidity transfer of the building envelope, but he assumed that the water inside the wall was only in the form of water vapor. However, the actual water's transfer includes both liquid water and water vapor. Künzel [8] considered that the diffusion of vapor in building materials is mainly transmitted in large pores, while the liquid water transfer mainly occurs in the pore surface, cracks and small pores. Based on this, Luikov[9] considered the water transfers under capillary force and in the form of vapor diffusion. Combined with Fourier's law, Fick's law and Darcy's law, Luikov proposed a model about the coupled heat and moisture transfer. The equation for the heat and moisture transfer model in COMSOL is based on the heat and humidity transfer in. The simulation of heat and moisture transfer is carried out based on this model. The model equation is as follows:

$$\rho C_P \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T + L_V \delta_P \nabla (\phi P_{sat})) = Q \quad (1)$$

$$\xi \frac{\partial \phi}{\partial t} - \nabla \cdot (\xi D_w \nabla \phi + \delta_P \nabla (\phi P_{sat})) = G \quad (2)$$

Among them, C_P is the volumetric heat capacity at constant pressure, $J/(m^3 \cdot K)$; T is the temperature, K ; k is the thermal conductivity, $W/(m \cdot K)$; L_V is the latent heat of evaporation, J/kg ; Φ is the relative humidity, 1 ; δ_P is the vapor permeability, s ; P_{sat} is the vapor saturation pressure, Pa ; ξ is the moisture storage capacity, kg/m^3 ; D_w is the moisture diffusivity, m^2/s ; Q is the heat source, $W/m^3 \cdot s$; G is the water vapor source, $kg/m^3 \cdot s$.

2.2.2 Mechanical control equation.

Most of the deformation caused by coupled temperature and humidity is small. In the case of small deformation, the mechanical equilibrium equation of the stress field can be expressed as:

$$\sigma_{ij,j} + F_i = 0 \quad (3)$$

In the formula, σ_{ij} is the stress generated by external load; F_i is the physical strength. The relationship between stress and displacement can be expressed by geometric equations, and the relationship between stress and deformation is closely related to relative displacement. Under the assumption of small displacement, the geometric equation is chosen as:

$$\varepsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (4)$$

In the formula, ε_{ij} is the strain, u is the displacement.

Combining the above control equations and considering the relationship and interaction of physical parameters, this paper uses the weak form solution of the partial differential equations of the Comsol Multiphysics software to give the most realistic results in theory.

2.3 boundary conditions

The model assumed that materials of each layer are homogeneous elastic and the stress field does not affect temperature and humidity fields. The model maintains the indoor temperature constant at $20^\circ C$, and the indoor relative humidity is constant at 0.5 . The outdoor temperature and relative humidity are obtained by the meteorological database in Hongqiao, Shanghai.

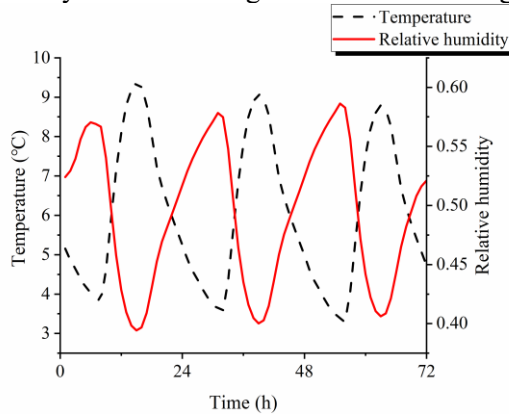


Figure 2. Temperature and Relative humidity in Hongqiao, Shanghai, January 1st-3rd.

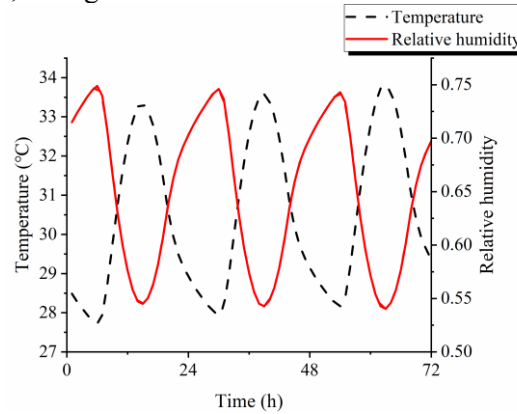


Figure 3. Temperature and Relative humidity in Hongqiao, Shanghai, July 1st-3rd.

This paper selects the environmental temperature and humidity data of January 1st-3rd and July 1st-3rd in Shanghai to study the deformation of the rock wool exterior insulation system during the periodic changes in temperature and humidity in winter and summer. The simulation time is 72 hours, and the time step is 1 hour. Figure 2 and Figure 3 show the temperature and relative humidity in the Shanghai Hongqiao area meteorological database.

2.4 physical parameters

Based on existing results, specifications and model studies, the material properties of each layer are

shown in Table 1.

Table 1. Material properties of each layer.

	Density	Heat capacity	Thermal conductivity	Young's modulus	Poisson's ratio	Thermal expansion coefficient	Wet expansion coefficient
	kg/m ³	J/(kg·K)	W/(m·K)	MPa	/	1/K	m ³ /kg
Coating mortar	1550	1025	0.91	4.6E3	0.28	1.1E-5	7.5E-6
Rock wool	150	750	0.039	9.1	0.1	6E-5	8E-8
Bonding mortar	1600	1050	0.93	4.9E3	0.28	1.2E-5	7.8E-6
Concrete	2500	882	1.37	2.55E4	0.2	1E-5	4.9E-6

3. Simulation results

In this paper, the deformation of the rock wool thermal insulation system has been measured by the development of stress and strain in three different layers.

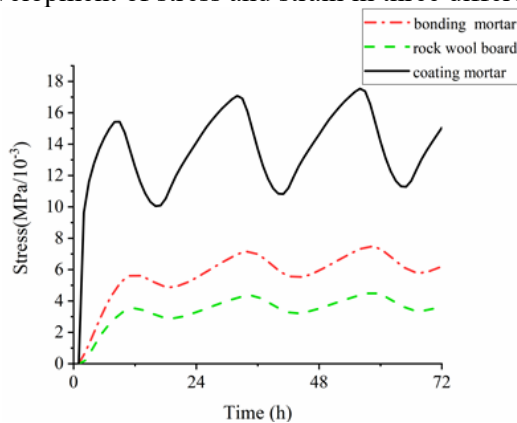


Figure 4. Stress development of rock wool external insulation system from January 1st-3rd.

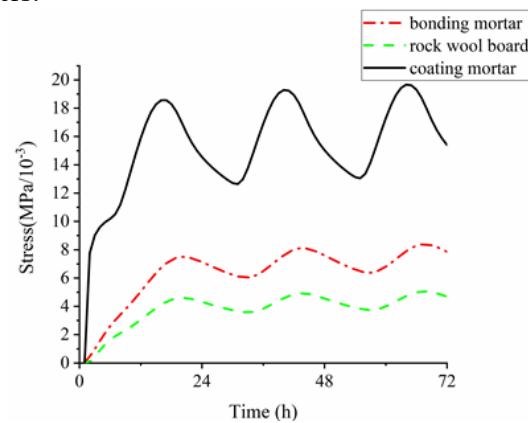


Figure 5. Stress development of rock wool external insulation system from July 1st-3rd.

Figure 4 shows the stress development with time in the different layers of the rock wool external insulation system from January 1st-3rd. As time progresses, the stress levels of the three layers fluctuate. According to the temperature and relative humidity data in Figure 2, when the time reaches 9 hours, 30 hours, and 55 hours, the temperature reaches the minimum value, the relative humidity reaches the maximum value, so the stress reaches a maximum. when the time reaches 18 hours, 42 hours, and 66 hours, the temperature reaches the maximum value, the relative humidity reaches the minimum value, so the stress reaches a minimum. The coating mortar has the highest stress, the maximum value can reach nearly 0.017MPa, and the thermal insulation board has the lowest stress. This is because the temperature and relative humidity of the coating mortar changes most violently with time, and the rock wool board has the smallest change in stress due to the good thermal insulation effect. Figure 5 shows the stress development with time in the different layers of the rock wool external insulation system from 0 to 72 hours. The stress changes in summer have the same regularity as in winter. However, because of the greater temperature and humidity difference, the maximum stress is greater in July 1st-3rd.

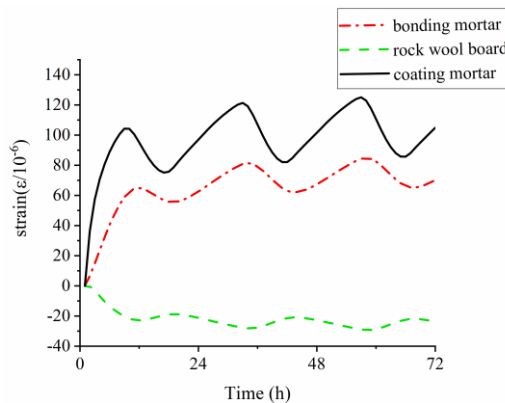


Figure 6. Strain development of rock wool external insulation system from January 1st-3rd.

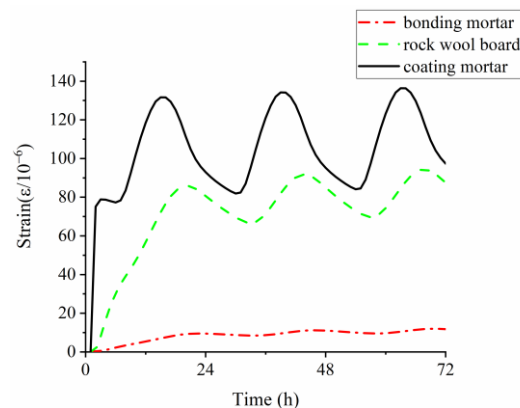


Figure 7. Strain development of rock wool external insulation system from July 1st-3rd.

Figure 6 shows the strain development with time in the different layers of the rock wool external insulation system from January 1st-3rd. As time progresses, the stress levels of the three layers fluctuate. As time progresses, the strain levels of the three layers fluctuate. According to the temperature and relative humidity data in Figure 2, when the time reaches 11 hours, 35 hours, and 59 hours, the strain reaches a maximum. when the time reaches 19 hours, 44 hours, and 65 hours, the stress reaches a minimum. The coating mortar and bonding mortar are both expanded and the rock wool board is shrunk. The coating mortar has the highest strain which can reach nearly 1.2×10^{-4} , and the rock wool board has the lowest strain which can reach nearly 3×10^{-5} . Figure 7 shows the strain development with time in the different layers of the rock wool external insulation system from July 1st-3rd. The strain changes in summer have the same regularity as in winter. However, in July 1st-3rd, the rock wool board is expanded, which is different from its performance in January 1st-3rd, for the outdoor temperature is higher than indoor temperature in summer and the outdoor temperature is lower than indoor temperature in winter. The coating mortar has the highest strain which can reach nearly 1.35×10^{-4} , and the bonding mortar has the lowest strain which can reach nearly 1×10^{-5} .

4. Conclusion

In this paper, the deformation of the rock wool thermal insulation systems under different climate conditions is compared and analyzed by the meteorological database from Shanghai. The results show that:

(1) With variation of temperature and relative humidity, the changes of stain and stress in coating mortar are much severe than that in the bonding mortar. In January 1st-3rd, the maximum stress of bonding mortar is 2.1 times of the maximum stress of coating mortar, and the maximum strain of bonding mortar is 1.5 times of the maximum strain of coating mortar. In July 1st-3rd, the maximum stress of bonding mortar is 2.3 times of the maximum stress of coating mortar, and the maximum strain of bonding mortar is 11.4 times of the maximum strain of coating mortar.

(2) The rock wool board has the lowest stress and strain compared with the bonding mortar and coating mortar.

(3) The development of strain and stress is fluctuated because of the variation of temperature and relative humidity, and their extremum values appear with the extreme value of temperature and relative humidity difference.

Acknowledgments

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