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Thermal Performance Simulation of CMA Concrete Composite Insulation Block

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Abstract. Cattle manure ash (CMA) is a pure, non-toxic and harmful component of biomass ash. In order to study the factors affecting the thermal performance of CMA concrete composite insulation block, single row hole, double row hole, dislocation double row hole and insulation material were used to replace the transverse wall of CMA concrete composite insulation block, and the thermal resistance values of each insulation block under different CMA content were studied. The results show that with the increase of CMA content, the thermal resistance of the block increases. Under the same cavity ratio, the smaller the width of the longitudinal rib, the greater the thermal resistance. After replacing the rock wool board and extradited polystyrene plastic board on the inside and outside transverse walls of the block, the thermal insulation performance is improved obviously, the relation between the thickness of replacement material and the thermal resistance of block is obtained.

Keywords. Cattle manure ash, insulation block, thermal resistance, heat transfer coefficient

1. Introduction

The recycling and utilization of livestock and poultry breeding wastes, namely, the recovery of useful resources and energy from livestock and poultry breeding wastes, has been a hot and difficult issue in recent years [1-2]. Among them, the burning of livestock and poultry breeding wastes for power generation has become one of the important ways for countries in the world to develop "low carbon economy" [3]. Studies have shown that the biomass ash produced after the combustion of livestock and poultry breeding wastes contains a certain amount of composition similar to volcanic ash, which can be applied in the production of building materials [4]. In the cold and pastoral regions of northwest China, cow Manure is an important resource as fuel for daily life. As a result, a large number of CMA is produced after burning cow Manure, which is generally treated as dumping, which is not conducive to resource recycling and easily causes environmental harm [5]. The engineering application of CMA can not only realize the reuse of livestock and poultry breeding wastes, effectively reduce the production and consumption of cement, and achieve the purpose of green environmental protection, but also ensure the strength of concrete made by CMA with low thermal conductivity [6]. For example, Sahin et al. used 5%-30% cow

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dung ash to replace cement in concrete and studied the properties of cow dung ash concrete. The experiments showed that cow dung ash concrete had good mechanical properties [7]. Zhou et al. measured the pozzolanic activity of cow dung ash (CMA), and the results showed that CMA had good pozzolanic activity, which verified the feasibility of CMA replacing cement to a certain extent [8]. Chen et al. formulated a self-insulation concrete block with excellent performance by using CMA concrete, which proved the feasibility of CMA concrete as self-insulation block material [9]. However, due to the complex contradictory relationship among the thermal performance, compressive strength and bulk density of CMA concrete [10], the key to the application of CMA engineering is to study the self-insulation block of CMA concrete based on the best thermal performance, mechanical performance and bulk density. In view of the advantages of energy saving and environmental protection of composite insulation block as a building wall material, it has been widely used in building energy saving design. Based on the existing research results, CMA concrete was produced by replacing cement with appropriate amount of CMA, and the thermal conductivity of concrete with different CMA content was measured. In addition, four kinds of CMA composite insulation blocks are designed, and the influence of different CMA content, hole arrangement and amount of insulation material on the thermal performance of CMA concrete blocks is studied by COMSOL finite element software.

2. Experiment

2.1. Measurement of Raw Materials and Related Parameters

CMA composite insulation block material is divided into solid material, filling insulation material and replacement insulation material. The solid material is CMA concrete. In this paper, the mixing ratio of CMA concrete with 0%, 5%, 10% and 15% CMA is designed respectively by using the equivalent substitution method. The mixing ratio is shown in Table 1.

Table 1. Mix ratio of CMA concrete.

CMA content (%)	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Stone (kg/m^3)	CMA (kg/m^3)
0	175	398	566	1261	0
5	175	378.10	555.97	1237.48	19.90
10	175	358.20	545.6	1214.39	39.80
15	175	338.30	536.46	1194.05	59.70

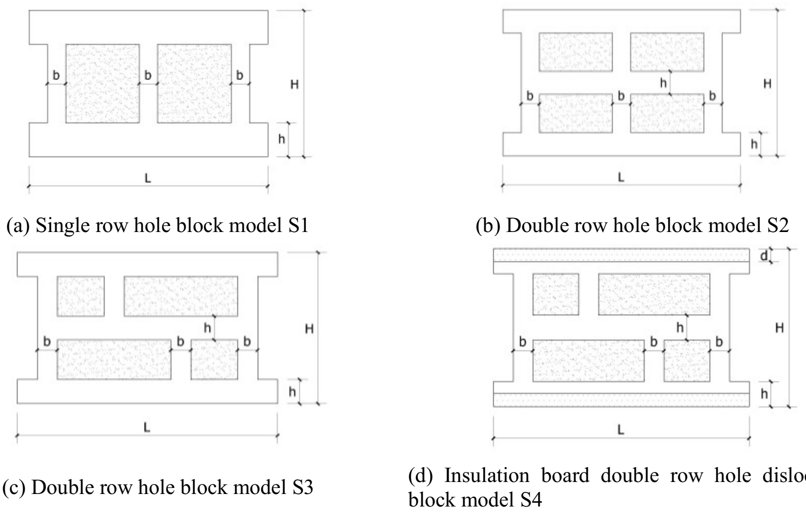
The thermal conductivity of CMA concrete with different mix ratios was measured using HR-4A concrete thermal physical parameter tester. The thermal conductivity of other materials was determined according to standard of *Code for Thermal Design of Civil Buildings* (GB 50176-2016), and the specific parameters were shown in Table 2.

Table 2. Thermal conductivity of material.

Wall composition	Materials	Heat conductivity coefficient [W/(m·K)]
The solid part of the block	Control concrete	1.5739
	Concrete mixed with 5% CMA	1.5655
	Concrete mixed with 10% CMA	1.5524
	Concrete mixed with 15% CMA	1.5241
Internal insulation part of the block	Polystyrene foam	0.039
Replacement of outer transverse wall of block	Pock wool board	0.041
Replacement of inner transverse wall of block	Extruded polystyrene foam board	0.030

2.2. Block Design

According to the standard of *Self-insulation Concrete Composite Block* (JGT 407-2013), the CMA concrete composite insulation block designed in this paper has an external size of 390 mm×240 mm×190 mm and a hole rate of 45% (Figure 1). In order to study the influence of the hole type on the heat transfer ability of the block, single row holes, double row holes and interlocking double row holes are designed. It is defined as types S1, S2 and S3, respectively. The solid material of the block is CMA concrete, and the insulation filling material is polystyrene foam. In order to consider the practical application of the wall, block S4 is designed. Rock wool board of a certain thickness is used as the substitute for the outer transverse wall, and extruded polystyrene foam board of a certain thickness is used as the substitute for the inner transverse wall.



(a) Single row hole block model S1

(b) Double row hole block model S2

(c) Double row hole block model S3

(d) Insulation board double row hole dislocation block model S4

Figure 1. Structure of composite insulation block.

In order to study the influence of different longitudinal rib widths b and transverse wall widths h on the heat transfer coefficient of the block under the same hole ratio

(45%), the width of longitudinal rib and transverse wall of the block designed in this experiment is shown in Table 3.

Table 3. Block numbering and dimensions.

Block type	b (mm)	h (mm)
S1-1	20	61.01
S1-2	25	58.42
S1-3	30	55.60
S1-4	35	52.50
S1-5	40	49.09
S2-1, S3-1, S4-1	20	41.72
S2-2, S3-2, S4-2	25	40.00
S2-3, S3-3, S4-3	30	38.11
S2-4, S3-4, S4-4	35	36.04
S2-5, S3-5, S4-5	40	33.75

2.3. Experimental Method

In this paper, the COMSOL finite element software is used to conduct the steady-state thermal simulation analysis of CMA concrete blocks. The process is as follows:

(1) According to the structure and size of the designed block, a finite element model was established, taking S2-3 as examples, as shown in Figure 2.

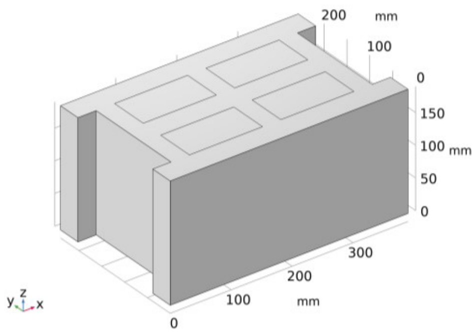


Figure 2. 3D model of block.

(2) The material properties of CMA concrete composite insulation block were defined.

(3) The physical field was set up. Block heat transfer study uses solid heat transfer physical field. Convective heat flux boundary condition is adopted for the inner and outer surfaces of the block, and adiabatic boundary is adopted for the other surfaces. According to the definition stipulated in *Code for Thermal Design of Civil Buildings* (GB 50176-2016), the specific thermal parameters in this area are shown in Table 4.

Table 4. Design parameters of thermal performance of block walls.

Outdoor calculated temperature (℃)	Indoor calculated temperature (℃)	Heat transfer coefficient of outer surface [W/(m²·K)]	Heat transfer coefficient of inner surface [W/(m²·K)]
-6.6	18	23	8.7

(4) The grid was constructed by using the grid sequence controlled by the physical field, and the grid division was shown in Figure 3.

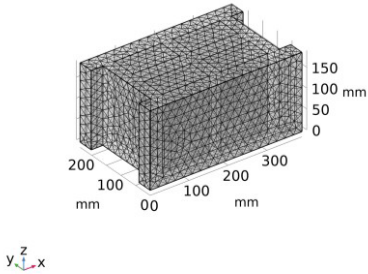


Figure 3. A sketch map of block model.

(5) The steady state calculation is carried out and the cloud map of heat flux is drawn. The average heat flow density q is obtained. To simulate the wall thermal conductivity experiment with the dual-heat flow meter method, THE average heat flow density of inner surface and outer surface is adopted in q. The thermal conductivity of the composite insulation block λ is calculated according to equation (1), and the thermal resistance R is calculated according to equation (2).

$$\lambda = \frac{q\delta}{t_1 - t_2} \tag{1}$$

$$R = \frac{\delta}{\lambda} \tag{2}$$

In the equation, λ is the overall thermal conductivity of the composite insulation block, W/(m·K); q is the mean heat flux of the inner and outer surfaces, W/m^2 ; δ is block thickness, m; t_1, t_2 are inner and outer surface temperatures, °C; R is thermal resistance of composite insulation block.

3. Results and Discussion

3.1. Effect of Pass on Thermal Resistance of Block

In this paper, the solid heat transfer physical field of COMSOL is used to analyze the single block. The heat conduction equation used in the program is as follows in equation (3). Since solid steady-state heat conduction research method is used in the analysis of the internal heat flow distribution of a single block, the influences of material density ρ, heat capacity Cp and velocity field u are not considered.

$$\rho C_p u \nabla T + \nabla \cdot (-\lambda \nabla T) = Q \tag{3}$$

In the equation, ∇ is the gradient operator; ∇T is the temperature gradient; Q is the heat source, W/m^3 ; u is the velocity vector, m/s ; C_P is the heat capacity at constant pressure, [J/(kg·K)]; ρ is the density, kg/m^3; F is the external force on the fluid per unit volume, N.

In order to study the influence of hole shape on the thermal resistance of blocks, blocks S1-3, S2-3 and S3-3 were taken to compare the thermal resistance values, and the solid material was CMA concrete with 5%CMA content. The results are shown in Table 5.

Table 5. Thermal parameters of different hole blocks.

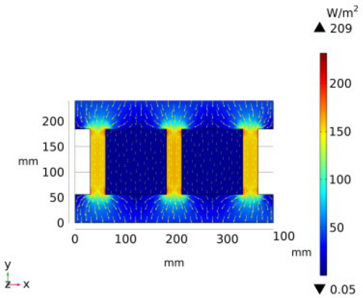
Block number	Inner side average heat flux (W/m^2)	Outside average heat flux (W/m^2)	Inner side average temperature (°C)	Outside average temperature (°C)	Thermal resistance (m^2·K/W)
S1-3	40.995	40.69	13.38	-4.85	0.446
S2-3	40.348	39.489	13.65	-4.95	0.466
S3-3	39.633	38.064	13.85	-5.03	0.486

It can be seen from Table 5 that the dislocation double-row hole block has the minimum average heat flux on the inside and outside, the maximum average temperature on the inside, the minimum average temperature on the outside and the maximum thermal resistance, so it has the best thermal insulation performance. The thermal resistance of the block with double row holes is increased by 4.5% compared with that of the block with single row holes. The thermal resistance of dislocation block with double row hole increases by 9.0% compared with that of double row hole block.

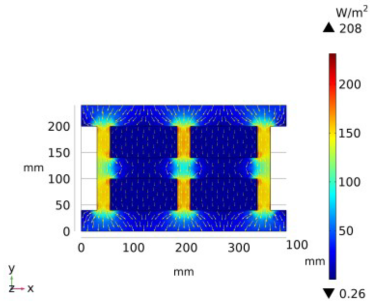
Figure 4 is the cloud chart of block heat flux of the model was obtained through calculation and solution. By comparing block S1 with block S2 in Figure 4, block S1 has no transverse ribs, the heat is mainly transferred longitude in the longitudinal ribs, while block S2 is composed of transverse ribs, and the heat in the longitudinal ribs is distributed to the transverse ribs, which partly reduces the heat flux conduction efficiency and improves the thermal resistance of the block. Compared with block S2 and S3, in S3, due to the dislocation of the middle longitudinal rib, the heat in the middle longitudinal rib is difficult to transfer, so more heat transfer is needed through the transverse rib to another longitudinal rib, so the heat transfer path is increased. Compared with block S2, the heat transfer efficiency is reduced even more. However, due to the dislocation of the middle longitudinal rib, the heat is concentrated in the edge longitudinal rib for transmission. It can be seen from the heat flux cloud map that the maximum heat flux of block S3 reaches 273W/m^2, which is concentrated in the left and right longitudinal ribs.

3.2. Effect of CMA Content on Thermal Resistance of Building Blocks

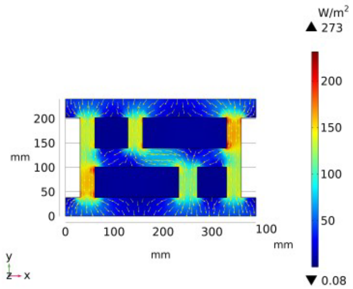
The thermal conductivity of concrete with 0%, 5%, 10% and 15% CMA content was imported into each block model. COMSOL was used to calculate the inner and outer heat flux of the block model as well as the average temperature of the inner and outer surfaces. The thermal resistance of a single block was obtained through equations (1) and (2). And the specific values are listed in Table 6.



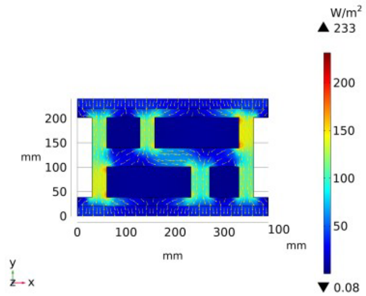
(a) Single row hole block S1 heat flux cloud image



(b) Double row hole block S2 heat flux cloud image



(c) Double row hole block S3 heat flux cloud image



(d) Double row hole block S4 heat flux cloud image

Figure 4. A cloud chart of block heat flux.

Table 6. Thermal resistance of block with different CMA content.

K (%)	Thermal resistance S1-1 (m^2·K/w)	Thermal resistance S2-1 (m^2·K/w)	Thermal resistance S3-1 (m^2·K/w)	Thermal resistance S4-1(m^2·K/w)
0	0.566	0.597	0.615	1.805
5	0.569	0.600	0.618	1.807
10	0.573	0.605	0.623	1.811
15	0.583	0.615	0.633	1.822

As can be seen from Table 6, with the increase of CMA content of concrete used in block solid material, the thermal resistance of blocks shows an upward trend and reaches the maximum value at 15%. In Figure 5, Δk is the increment value of CMA concrete block compared with the reference concrete block CMA content, and ΔR is the increment value of CMA concrete block compared with the reference concrete block thermal resistance. It can be seen from Figure 5 that, with the increase of CMA content, the added value of thermal resistance of masonry blocks increases, and the difference of the added value of thermal resistance of various types of blocks is more obvious. Among them, the added value of thermal resistance of S3-1 is the largest, indicating that the CMA content has the greatest influence on the thermal resistance of misplaced double-row hole blocks, and the increase trend of the added value of thermal resistance of each block is the most obvious when the content is 10%-15%. According to the above analysis, adding 15% CMA has the most obvious effect on improving the insulation capacity of the blocks.

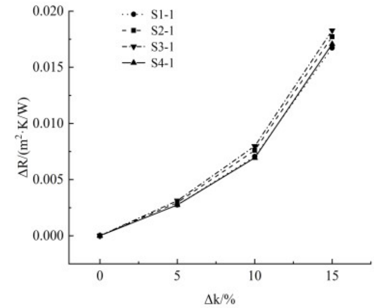


Figure 5. Effect of admixture increment on thermal resistance increment.

3.3. Influence of Rib Width of Block on Thermal Resistance

In order to study the influence of longitudinal rib width on thermal resistance value of single block with the same cavity ratio, block S1, S2, S3 and S4 with 5% CMA content were selected to conduct thermal resistance analysis of single block with different longitudinal rib width. It can be seen from Figure 6 that the thermal resistance of block S1 decreases from 0.569 m^2·K/W to 0.375 m^2·K/W, decreasing by 51.7%, as the width of the longitudinal ribs of the block increases. The thermal resistance of block S2 decreases from 0.60 m^2·K/W to 0.384 m^2·K/W, which decreases by 36.0%. The thermal resistance of block S3 decreases from 0.618 m^2·K/W to 0.406 m^2·K/W, which decreases by 34.3%. The thermal resistance of block S4 decreases from 1.822 m^2·K/W to 1.617 m^2·K/W, which decreases by 11.3%. Compared with blocks S1 and S2, the thermal resistance difference between them decreases gradually from 0.031 m^2·K/W to 0.009 m^2·K/W with the decrease of longitudinal rib width; while compared with blocks S2 and S3, the thermal resistance difference between them increases gradually from 0.018 m^2·K/W to 0.021 m^2·K/W with the decrease of longitudinal rib width.

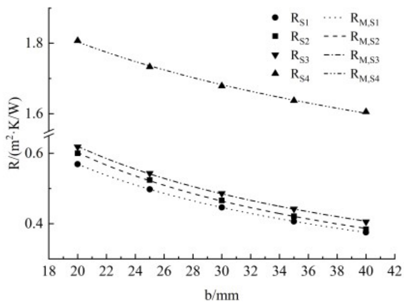


Figure 6. Influence of rib width of block on thermal resistance.

By fitting the test data, the equation for the influence of longitudinal rib width on the thermal resistance of different types of blocks can be obtained:

$$R_{b,S1} = 3.435b^{-0.6} \tag{4}$$

$$R_{b,S2} = 4.083b^{-0.639} \tag{5}$$

$$R_{b,S3} = 3.803b^{-0.606} \tag{6}$$

$$R_{b,S4} = 3.018b^{-0.142} \tag{7}$$

where $R_{b,S1}$, $R_{b,S2}$, $R_{b,S3}$, $R_{b,S4}$ are the thermal resistance of block S1, S2, S3 and S4 respectively, m²·K/W; b is the width of block rib, mm; R^2 is the goodness of the formula used for fitting; R^2 of equation (4) is 1, R^2 of equation (5) is 0.99948, R^2 of equation (6) is 0.99965, R^2 of equation (7) is 0.99788.

4. Conclusions

(1) Heat flow in CMA composite insulation block is mainly transferred in longitudinal ribs. When the longitudinal ribs are interlocked, the heat flow of the longitudinal ribs needs to be transferred through the transverse ribs, and the increase of heat transfer distance increases the thermal resistance of the block. When the width of longitudinal rib of block decreases, the thermal resistance of block increases. The relationship between thermal resistance and longitudinal rib width of composite insulation block was obtained by COMSOL numerical simulation.

(2) With the increase of CMA content, the thermal resistance value of composite thermal insulation block increases and reaches the maximum value when the CMA content is 15%. The effect on the thermal performance of the block is most obvious when the CMA content is 10%-15%.

(3) Under the condition that the hole rate is 45%, the CMA composite insulation block with the best thermal insulation performance is designed: the staggered double-row hole block is adopted, the solid material is CMA concrete with a CMA content of 15%, the longitudinal rib width b is 20 mm, the transverse wall width h is 41.72 mm, and the transverse wall replacement material thickness d is 30 mm. The heat transfer coefficient of the wall is 0.674 W/(m²·K).

Acknowledgments

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