

Research on multi-objective function optimization of self insulation hollow block structure based on genetic algorithm

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Abstract: Considering the multi-objective characteristics of the self insulation hollow block optimization problem, the thermal performance objective function, the mechanical performance objective function and the economic performance objective function are established for the self insulation block. The multi-objective function optimization method based on genetic algorithm is used to optimize the thermal performance, mechanical performance and economy of the hollow block. The opening rate, heat transfer coefficient and compressive strength of the three row interlaced hollow block, four row of staggered hollow block and five row of staggered hollow block were analyzed by using the ABAQUS finite element software. The results show that the opening rate of the five row staggered holes is 38.9% and the heat transfer coefficient is $0.592 W / (m^2 \cdot K)$. The insulation performance of the three and four row hollow blocks is better and the compressive strength is $10.23 Mpa$, which meets the strength requirement of the bearing structure.

1. Introduction

With the improvement of people living standards, their requirements for life comfort are getting higher, and building energy consumption is also growing [1]. At present, building energy consumption accounts for more than 30% of the total energy consumption of the society, which is one of the important causes of environmental problems such as water pollution, aggravated haze and global warming [2]. The external building envelope brings about the greatest energy loss in the building. Therefore, the innovation and development of building wall energy-saving technology is the most important part of building energy-saving work, and the improvement of the thermal insulation performance of building exterior walls can effectively achieve the goal of building energy conservation [3, 4]. Currently, there are two main ways of building wall insulation in China: internal insulation and external insulation. Among them, the internal insulation system of exterior wall has poor thermal stability and large thermal stress, tends to generate heat bridges, reduces house usable space, etc. External thermal insulation is beneficial to eliminate or weaken the thermal bridge, but some problems such as complicated construction and poor durability exist. Consequently, it requires to vigorously develop self-insulation wall materials to reduce the thermal conductivity of the envelope structure and achieve the goal of energy conservation [5]. The self-insulation blocks have the advantages of energy saving, soil conservation, waste utilization, environmental protection and higher production efficiency. With the implementation of China's national policy of energy conservation and emission reduction, building energy conservation has earned high attention from researchers, and



vigorous development of self-insulation blocks is the development direction of building block industry [6,7].

Recently, many domestic scholars have designed various hole structures to explore the reasonable holes distribution of concrete self-insulation blocks, and changed the number of hole rows, the hollow ratio and the hollow shapes by reasonable arrangement of the air layer. Combined with the finite element analysis software, the heat transfer coefficient and compressive strength of various self-insulation blocks are solved, and the structural optimization of self-insulation blocks is carried out by comparative analysis [8-10]. However, no mathematical methods have been used to establish a mathematical model to comprehensively optimize the thermal, mechanical and economic performance of the self-insulation block structure. Since engineering optimization issues in practice are more of multiobjective problems with complex constraints, it is especially important to research a constrained multi-objective optimization algorithm that is simple, effective and suitable for self-insulation hollow blocks.

Based on genetic algorithm, this paper established a multi-objective function of thermal performance, mechanical performance and economy, to optimize the structure of self-insulation blocks and obtain a self-insulation hollow block with better comprehensive performance. Through the simulation of the heat transfer coefficient and compressive strength of the self-insulation blocks with the finite element software ABAQUS, the reliability and rationality of the self-insulation hollow block structure optimized by the multi-objective function based on genetic algorithm were verified, and simultaneously self-insulation concrete hollow blocks which satisfied the requirements of energy saving and load-bearing were obtained.

2. Multiobjective optimization model and optimization algorithm

In the actual engineering application, multiobjective optimization problems are often encountered. Each objective function cannot be compared or even conflict with each other, and in the process of optimization, multiple objective functions need to be considered to simultaneous optimization. Genetic algorithm is a global optimization algorithm developed in recent years, and widely used in various complex optimization problems thanks to its implicit parallelism, randomness and high robustness.

2.1. Multiobjective optimization model

The general multiobjective optimization issues consist of a set of objective functions and related constraints, which can be described as follows [11]:

$$\min_{x \in \Omega} F(x) = [f_1(x), f_2(x), \dots, f_m(x)] \quad (1)$$

$$x \in \Omega \subset R^n \quad (2)$$

$$s.t. \begin{cases} lb \leq x \leq ub \\ Aeq * x = beq \\ A * x \leq b \end{cases} \quad (3)$$

where $f_i(x)$ is the target sub-function to be optimized, and they conflicted with each other; x is the variable to be optimized, $x = (x_1, x_2, \dots, x_n)^T$ is the n-dimensional vector of R^n space, the space D where x is located called the decision space of the issue; lb and ub are the upper and lower bounds of the variable x , respectively; $Aeq * x = beq$ is the linear equality constraint of the variable x ; $A * x \leq b$ is the linear inequality constraint of the variable x . We refer to the solution in the decision space that minimizes the objective function as the optimal solution. Usually, there is no certain optimal solution, but an optimal solution set.

2.2. Genetic algorithm

The Genetic Algorithm (GA) is a kind of bionic optimization algorithm first created in 1975 by Professor J. Holland of the University of Michigan in the United States [12]. It is a search algorithm

based on Darwin's biological evolution theory and Mendel's theory of genetic variation, simulating the process of biological evolution, and self-adapting heuristic global optimization. Since the genetic algorithm does not need to consider the dynamic information of the issue too much, like continuousness and differential, the algorithm has a simple structure and the advantages of global search capability, implicit parallelism of information processing, robustness and scalability. Genetic algorithms provide a common framework for solving complex system optimization problems, independent on the field and type of the issue. Based on the fitness function, the genetic algorithm implements an iterative process of individual structure reorganization within a group by applying genetic operations to individuals in the population. Goldberg's basic genetic algorithm (also known as standard genetic algorithm, simple genetic algorithm, SGA) is a basic genetic algorithm [13], including three basic genetic operators of selection, crossover and mutation. Equation (4) is the mathematical model of the basic genetic algorithms. It breaks through the framework of the original optimization method in thinking, especially suitable for dealing with complex and nonlinear problems that are difficult to solve by traditional search methods. Nowadays it has been widely used in the fields of combinatorial optimization, machine learning, adaptive control and planning design, and has a good application in economics and decision-making, serving as one of the key technologies about intelligent computing in the 21st century [14-17].

The basic genetic algorithm can be formally described as follows:

$$SGA = (C, E, P_0, N, \Phi, \Gamma, \Psi, T) \quad (4)$$

where: C —individual coding method

E —Individual fitness evaluation function

P_0 —Initial population

N —Population size

Φ —selection operator

Γ —crossover operator

Ψ —mutation operator

T —genetic algorithm terminated condition

3. Multiobjective function establishment of self-insulation block

The author took the block A produced by a company in Shaanxi Province shown in Fig. 1 as the research object, and the outline dimensions: length \times width \times height was 390 mm \times 190 mm \times 190 mm. On the assumption that the top and bottom of the composite block outside surface are insulated and the temperature of a specific uniform surface was specified on the front and rear sides, it was simplified to the static two-dimensional stable heat transfer shown in Fig. 2 [18]. A two-dimensional model was established, and the thermal analysis unit was selected by finite element software ABAQUS. As presented in Fig. 2, the heat flux density is the densest in the longitudinal ribs of the block, where ordinary concrete is, with obvious heat bridge effect. The reason for this phenomenon is that the temperature difference between the front and rear sides of the block is comparatively large, and the thermal conductivity of foam concrete is quite different from that of ordinary concrete. It can be seen that, under the same dimensions, the increase of the longitudinal ribs length makes the length of the heat transfer path extended, the heat flow density lowered, and the thermal resistance of the block risen. It verifies that the hollows are staggered, the increase of the heat transfer path length grows the thermal resistance, which can improve the thermal insulation performance of self-insulation blocks [8, 9, 19, 20].

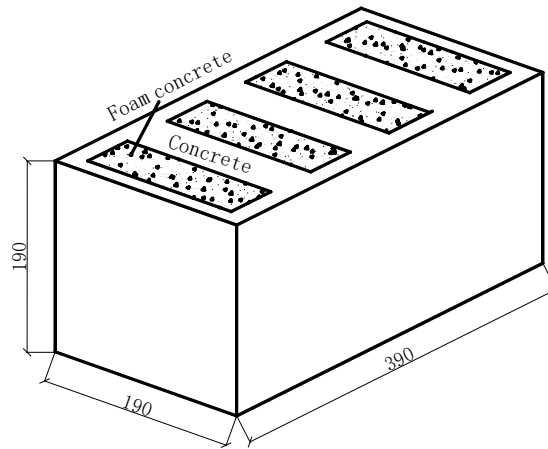


Fig 1. Three-dimensional structure of block A

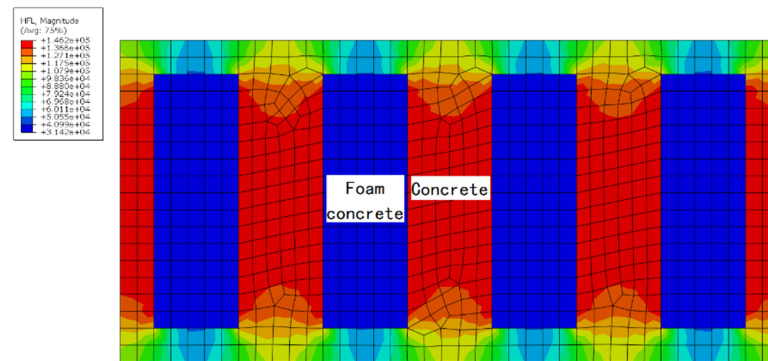


Fig 2. Two-dimensional heat flux distribution map of block A

Due to the wide variety of self-insulation blocks, the basic principle of selecting self-insulation block is: to ensure that the self-insulation blocks have reliable mechanical properties and good thermal performance [1]. Concrete was chosen as the base material with a thermal conductivity of $1.7 \text{ W/(m}\cdot\text{k)}$. According to the "self-insulation concrete composite block" (JG/T 407-2013), the dimensions of the block are determined: length \times width \times height of $390\text{mm} \times 190\text{mm} \times 190\text{mm}$, as shown in Figure 3. The inner wall width is the same between each row of holes. The inner wall paralleling to the length direction is called a transverse rib, and the rib width is g . Assuming that the inner wall width between each column of holes is the same, the inner wall paralleling to the width direction of the block is called a vertical rib, and the rib width is c . The length of the large rectangle in each row of staggered holes is b and the width is f ; the length of the small rectangle in each row of staggered holes is d and the width is f . In order to meet the requirements of the specification "the minimum outer wall thickness of self-bearing wall block is 15mm", the outer wall thickness of the block is set to 20mm.

The three-row, four-row, and five-row staggered rectangular holes are respectively optimized, and three row staggered holes are taken as an example. The three-dimensional structure diagram of Fig. 3 is simplified to the two-dimensional plan view shown in Fig 4. Taking the apex of the self-insulation hollow block as the coordinate origin, AB as the axis, AD as the axis, the plane rectangular coordinate system is established. In Fig. 4, $S_{T_1} = S_{T_2} = S_{T_3}$, $S_{W_1} = S_{W_2} = S_{W_3}$, while S_i stands for the hole area). A heat bridge is formed by heat transfer through the vertical ribs, and the heat transfer path is along the center line of the vertical rib, shown as the dotted line in Fig. 4.

The multiobjective optimization method adopts the genetic algorithm, that is, the objective function is established according to each target, and the established multiobjective function is employed to solve the function optimization problem through the MATLAB environment, with the given constraint

condition. The objective function is established by thermal performance, mechanical performance and economy. According to the heat bridge formed by heat conduction in the self-insulation hollow block, the objective function is built with the length of the heat transfer path as the thermal performance. According to the heat bridge formed by heat conduction in the self-insulation hollow block, the thermal performance is based on the objective function built with the length of the heat transfer path. As shown in Fig. 5, the center position coordinate of the first-row vertical rib is $E(x_1, y_1)$, the second-row coordinate is $F(x_2, y_2)$, and the center position coordinate of the third-row vertical rib is $G(x_3, y_3)$. In accordance with the shortest line segment between two points, it is simplified to find the line distance between $E(x_1, y_1)$, $F(x_2, y_2)$ and $G(x_3, y_3)$. Fig. 5 is the simplified road map, the function of $f_1(x)$. The mechanical performance takes the ratio of the vertical rib to the entire self-insulation block as the objective function, namely $f_2(x)$. Economic performance is based on the opening rate to establish the objective function, that is the function $f_3(x)$. Equations (5) ~ (9) are the established mathematical models of multiobjective functions.

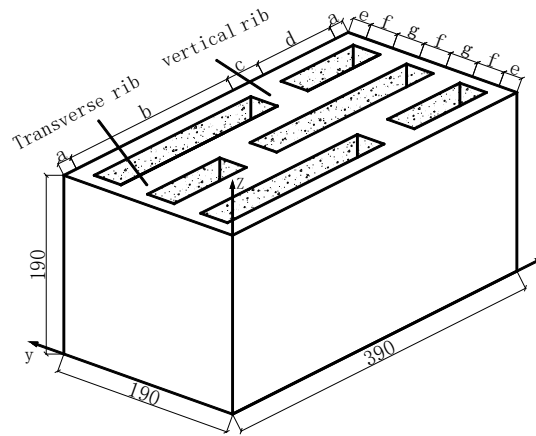


Fig 3. Three-dimensional structure diagram of three row staggered holes of the self-insulation blocks

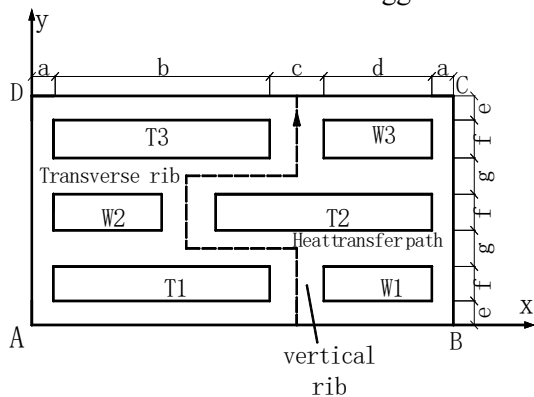


Fig 4. Heat transfer path plane graph of three row staggered holes

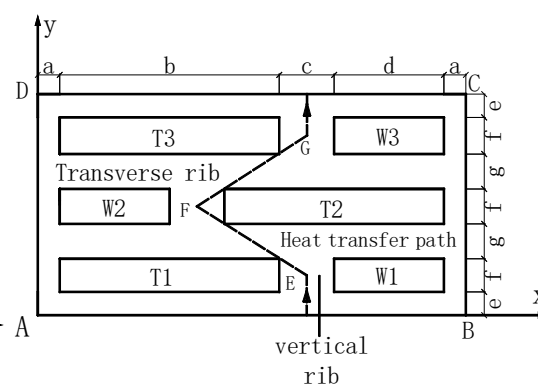


Fig 5. Plane graph of three row staggered holes after simplified heat transfer path

3.1. Mathematical model:

- Thermal performance objective function:

$$f_1(x) = y_1 + \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} + \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2} + (190 - y_3) \quad (5)$$

- Mechanical performance objective function:

$$f_2(x) = \frac{3cf + 700g}{390 \times 190} \quad (6)$$

• Economic evaluation objective function:

$$f_3(x) = \frac{bf + df}{130 \times 190} \quad (7)$$

• Constraints:

$$\textcircled{1} \begin{cases} x_1 = \frac{390 + b - d}{2} \\ x_2 = \frac{390 - b + d}{2} \\ x_3 = \frac{390 + b - d}{2} \end{cases} \quad \textcircled{2} \begin{cases} y_1 = 20 + \frac{f}{2} \\ y_2 = 20 + \frac{3}{2}f + g \\ y_3 = 20 + \frac{5f}{2} + 2g \end{cases} \quad \textcircled{3} \begin{cases} 0 < f < 35 \\ 0 < g < 35 \\ a = e = 20 \\ 3f + 2g = 150 \\ b + c + d = 350 \end{cases} \quad (8)$$

$$\textcircled{4} \begin{cases} S_{T_1} = S_{T_2} = S_{T_3} \\ S_{W_1} = S_{W_2} = S_{W_3} \\ S_{T_i} > S_{W_i} > cf \end{cases} \quad \textcircled{5} \begin{cases} 175 < b < 350 \\ 0 < c < 60 \\ 0 < d < 175 \\ b > d \end{cases} \quad (9)$$

In this paper, to find the largest solution of the objective function $f_1(x)$, $f_2(x)$ and $f_3(x)$, for the maximization problem, the objective function can be multiplied by (-1) and transformed into a problem of minimum solution.

4. Analysis of multiobjective optimization results

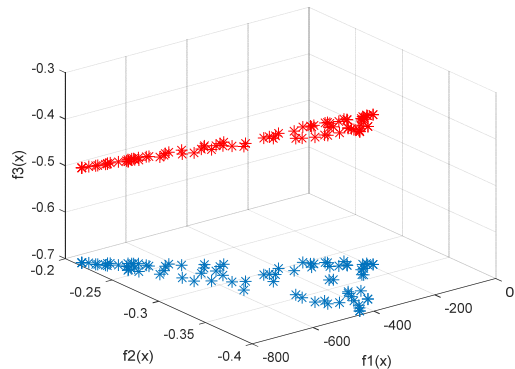


Fig 6. Three-dimensional diagram of multiobjective function values of three row staggered holes

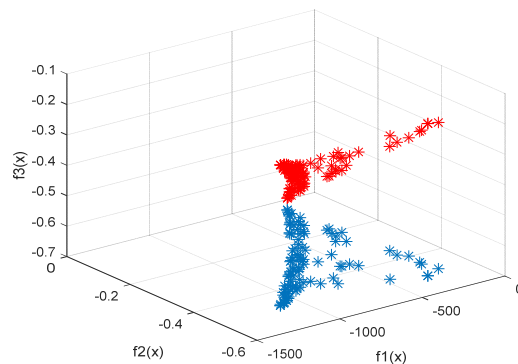


Fig 7. Three-dimensional diagram of multiobjective function values of four row staggered holes

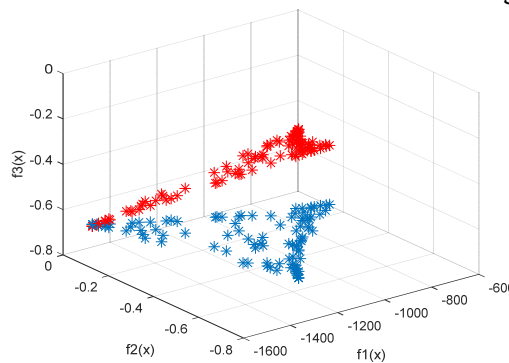


Fig 8. Three-dimensional diagram of multiobjective function values of five row staggered holes

The MATLAB genetic algorithm toolbox was used to iterate the functions 1000 times, with the population size of 100 and the precision of $1e(-5000000)$. Optimization of the objective functions $f_1(x)$, $f_2(x)$ and $f_3(x)$ can obtain an optimal solution set of 85. As shown in Fig. 6, the X axis represents the value of the objective function $f_1(x)$, the Y axis represents the value of the objective function $f_2(x)$, and the Z axis represents the value of the objective function $f_3(x)$. Red * represents the value of the multiobjective function and blue is the value mapped on the plane. Due to the randomness of each operation by the genetic algorithm, the highest proportion of solutions is obtained after multiple operations. At this moment, $f_1(x)=-675.538$, $f_2(x)=-0.3613$, $f_3(x)=-0.453$, and a set of solutions of the corresponding independent variable $b=230$, $c=40$, $d=80$ and $c=f=30$ can be acquired, with the resulting structure shown in Fig. 9. Similarly, under the same structure dimensions of the self-insulation block, the optimized multiobjective function values of the four row staggered holes are obtained and displayed in Fig. 7. After multiple operation, the highest proportion of solution is achieved, at this moment $f_1(x)=-1120.483$, $f_2(x)=-0.425$, $f_3(x)=-0.389$, and the optimal solution is: the structure of $b = 225$, $c = 40$, $d = 85$, $f = 22.5$, $g=20$, shown as Fig. 10. The multiobjective function value after optimization of five row staggered holes is displayed in Fig. 8. After multiple calculations, a set of solution at the highest proportion is acquired, at this moment $f_1(x)=-1285.674$, $f_2(x)=-0.425$, $f_3(x)=-0.389$, while the solution of the independent variable could be obtained: $b=220$, $c=45$, $d=85$, $f=18$, $g=15$. The structure is exhibited in Fig. 11.

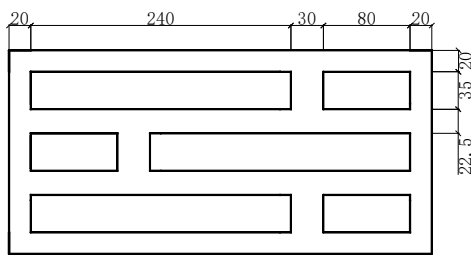


Fig 9. Structure of the three row staggered holes after optimization

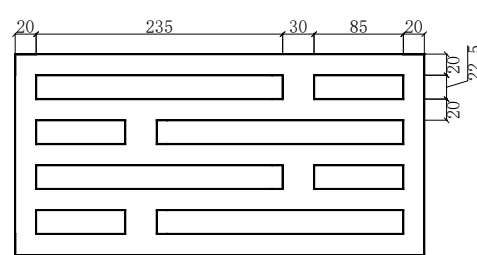


Fig 10. Structure of the four row staggered holes after optimization

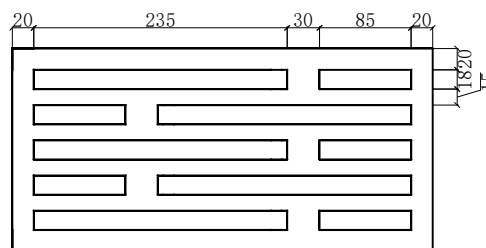


Fig 11. Structure of the five row staggered holes after optimization

5. Numerical simulation analysis of self-insulation block structure performance

For the multiobjective functions establishment based on the above genetic algorithm, the structure of the self-insulation block was optimized. The optimized self-insulation blocks were numerically simulated by ABAQUS finite element software for comparative analysis, and the self-insulation blocks with better structural performance were obtained, verifying the rationality and feasibility of genetic algorithm for self-insulation block structure optimization at the meantime.

Mathematic model: owe to the relatively uniform distribution of the indoor and outdoor temperature, the heat transfer from the self-insulation block could be regarded as steady-state heat transfer without heat source inside the wall, and the three-dimensional heat conduction differential equation could be expressed in the form of equation (10):

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (10)$$

Boundary conditions: ABAQUS is selected for numerical simulation analysis. It was assumed that the temperature boundary conditions were set at both ends of the block, that was the temperature difference generated between the front and back face of the block, giving rise to heat transfer; the initial temperature was set to 25°C , $L_1 = 390\text{mm}$, $L_2 = 190\text{mm}$, $T_1 = 50^\circ\text{C}$, $T_2 = 20^\circ\text{C}$. The left, right, up and down faces of the block were set as adiabatic boundary conditions, that was the heat in and out equal on the four faces, and (11) is the heat balance formula. According to the experimental results, combined with the empirical and theoretical calculation results, the thermal conductivity of self-insulation block concrete material is $1.7\text{W}/(\text{m}\cdot\text{k})$, the density is $2200\text{kg}/\text{m}^3$, and the concrete specific heat capacity is $920\text{J}/(\text{kg}\cdot\text{k})$. The three-dimensional model of the optimized three row staggered holes built by ABAQUS is shown in Fig. 12.

$$\begin{aligned} x=0, \frac{\partial T}{\partial x} &= 0 \\ x=L_1, \frac{\partial T}{\partial x} &= 0 \\ y=0, \frac{\partial T}{\partial y} &= T_1 \\ y=L_2, \frac{\partial T}{\partial y} &= T_2 \\ z=0, \frac{\partial T}{\partial z} &= 0 \\ z=L_3, \frac{\partial T}{\partial z} &= 0 \end{aligned} \quad (11)$$

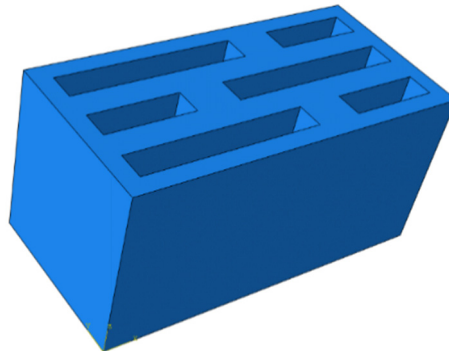


Fig 12. Three-dimensional finite element model of the three row staggered holes after optimization

Table 1. Numerical simulation results of self-insulation block structure performance

Block type	Opening rate	thermal resistance $\text{m}^2 \cdot \text{K} / \text{W}$	heat transfer coefficient $\text{W} / (\text{m}^2 \cdot \text{K})$	compressive strength Mpa
Three row	45.3%	1.3831	0.723	9.21
Four row	38.9%	1.5361	0.651	10.25
Five row	38.9%	1.9193	0.521	10.23

It can be obtained from Table 1 that, for the self-insulation block structure optimized by genetic

algorithm, the three row staggered holes have an opening ratio of 45.3%, a heat transfer coefficient of $0.723 \text{ W} / (\text{m}^2 \cdot \text{K})$, and a compressive strength of 9.21 Mpa ; The opening rate of the four row staggered holes is 38.9%, which is 14.1% lower than that of the three row staggered holes. The heat transfer coefficient is $0.651 \text{ W} / (\text{m}^2 \cdot \text{K})$, which is 9.96% lower than that of the three row staggered holes, while the compressive strength is 10.25 Mpa , which is increased by 11.3% compared with that of three row staggered holes; The opening rate of the five row staggered holes is 38.9%, which is 14.1% lower than that of the three row staggered holes. The heat transfer coefficient is $0.521 \text{ W} / (\text{m}^2 \cdot \text{K})$, 27.9% lower than that of the three row staggered holes, while the compressive strength is 10.23 Mpa , increased by 11.1% compared with that of three row staggered holes. It can be seen from the above analysis that for the optimized self-insulation hollow block, with the increase of the hole rows number, the heat transfer coefficient is gradually reduced, and the thermal insulation performance of the block is better; as the opening rate increases, the compressive strength decreases.

6. Conclusion

Based on the genetic algorithm, a multiobjective function was established. By combining three factors of thermal performance, mechanical performance and economy of the self-insulation block, self-insulation concrete hollow blocks of five row staggered holes were designed. Through the finite element numerical simulation by ABAQUS, the reliability and rationality of self-insulation block concrete hollow blocks structure optimized by the genetic algorithm were verified, which provides a new idea and method of optimizing the self-insulation block structure.

By increasing the heat flux transfer length, the thermal resistance could be effectively increased, the thermal insulation performance of the self-insulation block would be improved, the thermal bridge effect could be slowed down, and the heat transfer coefficient of the block could be reduced.

The multiobjective performance optimization method was used to comprehensively optimize the thermal performance, mechanical performance and economic performance of the block. Finally, through the comparative analysis, the self-insulation block type of five row staggered holes was obtained, with the heat transfer coefficient of $0.521 \text{ W} / (\text{m}^2 \cdot \text{K})$, the compressive strength of 10.23 Mpa . The MU10 strength standard was achieved, which was used as a load-bearing structure and met the goal of energy saving by self-insulation concrete hollow block wall at the meantime.

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