Simulation of Thermal Behavior in Hollow-glass-microsphere-filled Cement Composites

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Abstract

In this paper, thermal behavior in cement composites filled with hollow glass microspheres was modeled by finite element method based on heat conduction theory. According to experimental observation of the microsphere distribution in the cement matrix material by the scanning electron microscope, a two-dimensional unite cell including single hollow glass microsphere and cement material phase is chosen as the computational model, in which the specified temperature conditions are applied on the opposite edges of the cell to model heat transfer in the cell by finite element simulation. The effects of volume content and wall thickness of the microsphere, thermal conductivities of the wall and the cement on the effective thermal conductivity of the composite are investigated. Numerical results demonstrate that the developing lightweight cement-based composite can have significant lower thermal conductivity than the cement matrix itself by introducing the hollow glass microsphere.

Keywords: Hollow glass microsphere; Cement; Composite; Thermal conductivity; Finite element method

1. Introduction

Cement-based materials have become one of the most widely used construction materials because of their significant advantages as good performance, machinability, low cost, et.al (Balaguru and Shah, 1992). In order to improve thermal or mechanical properties of cement materials, various cement composites were developed by filling steel fibers (Gao et al., 1997; Shannag et al., 1997), natural fibers (Pandey et al., 2010; Savastano Jr et al., 2009), synthetic fibers including aramid, high-strength high-modulus polyethylene, and polypropylene (Wang et al., 1990; Silva et al., 2013), industrial waste like fly ash (Li and Wu, 2005; Donatello et al., 2014) and tyre rubber particles (Segre and Joekes, 2000; Huang et al., 2013), and so on. From the viewpoint of the reduction of energy consumption in construction materials, the development of lightweight cement composites with low thermal conductivity will be interesting.

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In this study, we focus on the use of hollow glass microspheres to construct lightweight cement composites with lower thermal conductivity than that of the single cement material phase. The used hollow glass microsphere with small size in micrometer scale usually has very thin wall enclosing an inert gas so that it has excellent physical properties such as low density and low thermal conductivity. Thus, it's very suitable for the development of lightweight and low thermal conductivity cement composites. In this context, some works have been conducted. For example, Kan and Demirboğa (2007) studied the compressive strength of concretes made up of mixtures of expanded polystyrene beads and cement. Miao et al. (2012) developed a lightweight cement composite material consisting of expanded polystyrene beads, the hydraulic sand from the Yangtze River and cement and tested its mechanical properties. Park (2012) investigated the effect of local void formation arising from gas hydrate dissociation, loss of fine particles, or dissolution of vanishing materials in composites consisting of glass beads, cement and water. More recently, the fly ash microsphere (FAM) was added as filler into cement to improve packing density, flowability and strength of cement paste (Kwan and Chen, 2013).

In this work, the idea is to use the H60 hollow glass microsphere provided by the supplier as raw material, which has an approximated average diameter 24.728 μm, to develop a lightweight construction cement-based composite with lower thermal conductivity so as to decrease the energy consumption by reducing heat transfer into buildings. Compared to the FAM, which has complex chemical compositions (Kwan and Chen, 2013), the major chemical composite of the used hollow glass microsphere is SiO₂ and thus it has more stable chemical property. Besides, the hollow glass microsphere has more uniform particle size than the FAM. Herein, finite element simulation (Bathe, 1996) is employed to investigate heat transfer behavior in the composite with the presence of hollow glass microsphere. Simultaneously, sensitivity analysis is performed to investigate the influences of some control parameters including volume content of the hollow glass microsphere, thickness of the wall, thermal conductivity of the wall and thermal conductivity of the cement on the effective thermal conductivity of the composite.

2. Micromechanical Model

2.1 Physical model

![Fig. 1. Scanning electron microscope (SEM) micrograph of the hollow-glass-microsphere filled cement composite (40% vol)](image)

Fig. 1 displays a scanning electron microscope (SEM) micrograph showing a typical microstructure of the cement composite (40% vol), which is fabricated by reasonable mixture of the hollow glass
microspheres. From the figure, it's observed that the microspheres disperse well in the cement matrix. So, we can suppose that the hollow glass microspheres are distributed uniformly in the cement resin, apart from the assumption of perfect bond between the microspheres and the cement. These assumptions significantly simplify the analysis procedure below.

Due to the geometrical symmetry, the practical three-dimensional (3D) heat transfer problem in the composite can be simplified as a two-dimensional (2D) heat transfer problem (Liang and Li, 2007). In their work, 2D and 3D hollow-glass-bead-filled polypropylene composite models were compared and it was found from numerical results that the values of effective thermal conductivity of the 3D composite model were just slightly higher than those of the 2D composite model. However, the 2D model has more simple geometry than the 3D model. Thus, in the study, a 2D hollow-glass-microsphere-filled cement composite model is taken into account. Fig. 2 displays a ternary unit cell model with side length L, which consists of three material phases: gas, wall of microsphere and cement. In Fig. 2, R represents the inner radius of the microsphere and t is the thickness of the wall. Due to very small wall thickness, the volume content of the hollow glass microsphere to the composite is approximately defined by

$$v_s = \frac{\pi R^2}{L \times L}$$

(1)

In the practical analysis, once the volume content $v_s$ of the microsphere is chosen, the side length of the unit cell can be calculated from Eq. (1).

2.2 Physical parameters

In this paper, cement composites filled with H60 hollow glass microspheres are considered. The H60 hollow glass microspheres were supplied by Sinosteel Maanshan New Material Technology Co., Ltd in China. The wall of microsphere is made of silicate and encloses a gas, which has smaller thermal conductivity than the wall. The average radius of H60 is 24.728μm. Table 1 listed some physical parameters of H60. Besides, the value of thermal conductivity of the cement resin is also tabulated in Table 1 as 0.93 W/m/K.
2.3 Effective thermal conductivity of composites

To evaluate the effective thermal conductivity of the composite, two different constant temperature boundary conditions \( T_0 \) and \( T_1 \) (\( T_0 > T_1 \)) are respectively applied on the opposite surfaces of the cell, i.e. the left and right surfaces, to make thermal currency flow through the cell from the left to the right. The remaining surfaces are assumed to keep insulated. Fig. 3 shows the specified boundary conditions along the cell boundary.

**Table 1** Basic properties of H60 hollow glass microspheres and cement matrix (Liang and Li, 2007)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>True density ( \rho \ (\text{g/cm}^3) )</td>
<td>0.59~0.63</td>
</tr>
<tr>
<td>Average inner diameter ( D=2R \ (\mu m) )</td>
<td>24.728</td>
</tr>
<tr>
<td>Average wall thickness ( t \ (\mu m) )</td>
<td>1.1095</td>
</tr>
<tr>
<td>Thermal conductivity of gas ( k_g \ (\text{W/mK}) )</td>
<td>0.0228</td>
</tr>
<tr>
<td>Thermal conductivity of wall ( k_w \ (\text{W/mK}) )</td>
<td>0.1793</td>
</tr>
<tr>
<td>Thermal conductivity of cement paste ( k_c \ (\text{W/mK}) )</td>
<td>0.93</td>
</tr>
</tbody>
</table>

![Fig. 3. Illustration of specified boundary conditions for (a) the unit cell and (b) the equivalent homogeneous medium](image)

According to the theory of heat conduction, the constitutive relation describing the heat flux and the temperature gradient can be given by (Rohsenow et al., 1997)

\[
q_i = -k_i \frac{\partial T}{\partial x_i} \quad (i = 1, 2)
\]  

in which \( q_i \) is the heat flux component along the \( x_i \)-direction, \( k_i \) the thermal conductivity along the \( x_i \)-direction, \( T \) the temperature variable.
In an equivalent homogeneous medium to the unit cell under consideration, as shown in Fig. 3, the boundary conditions applied along the cell boundary will result in linear temperature variation and constant heat flux component. For this case, the temperature gradient along the $x_1$-direction in the equivalent medium can be expressed as

$$\frac{\partial T}{\partial x_1} = -\frac{T_0 - T_1}{L}$$

(3)

Thus, the thermal conductivity of the equivalent medium, which is also the effective thermal conductivity of the composite, can be evaluated by (Wang and Qin, 2011; Qin and Wang, 2013)

$$k_{1\text{eff}} = \frac{q_1 L}{T_0 - T_1}$$

(4)

where $q_1$ represents the constant heat flux component in the equivalent medium and is practically approximated by the average value of the heat flux component $q_1$ on the left surface of the cell

$$q_1 = \frac{1}{L} \int_{-L/2}^{L/2} q_1(-L/2, y)dy$$

(5)

which can be evaluated by the trapezoidal numerical integral.

3. Finite Element Simulation and Results

3.1 Heat transfer in the composite

In order to investigate the influence of the presence of hollow glass microsphere on the temperature distribution in the cell, the case $v_s = 30\%$ is taken as an example. In the practical computation, the constant temperatures $T_0 = 30^\circ C$ and $T_1 = 10^\circ C$ are respectively imposed on the left and right surfaces of the cell. Fig. 4 shows a typical triangular mesh division implemented by ABAQUS, in which 572 triangular linear elements with 307 nodes are used to discretize the cell. The distributions of the temperature and the heat flux component $q_1$ are displayed in Fig. 5, in which the direction of the arrow indicates the direction of heat flow component and the length of the arrow represents the strength of the heat flow component. From Fig. 5, it’s seen that the presence of the microsphere significantly changes the temperature distribution to two-dimensional nonlinear distribution, and the temperature changes more quickly along the wall of the hollow glass microsphere than outside of the microsphere, compared to the case without the microsphere. Simultaneously, when the heat flow transferred into the cement through the left surface encounters the middle hollow glass microsphere, just a very small proportion of the heat carry flows through the inner gas region, while a great part of it passes through and round the wall of the microsphere, due to the low conductivity of the gas. In this case, the route of heat transfer in the composite become longer and complicated, leading to reduction of heat transfer properties of the composite.
3.2 Effect of the volume fraction of hollow glass microsphere

To investigate the influence of the microsphere volume content, we assume that the thickness of the microsphere wall, the inner radius of the microsphere and the thermal conductivities of the wall, gas and cement phases are directly taken to be the values given in Table 1. When the percent volume contents of the microsphere are 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50% and 60%, respectively, the change of the effective thermal conductivity of the composite is provided in Fig. 6. It’s clearly seen that the effective thermal conductivity of the composite is greatly influenced by the change of the microsphere volume content. Compared to the case in absence of microsphere, which corresponds to pure cement with thermal conductivity 0.93 W/m/K, there is 82.8% decrease of $k_1^{\text{eff}}$ as the microsphere volume content increases to 60%. Moreover, this decrease shows evident nonlinearity. Additionally, we also find that there is 0.4613 W/m/K decrease of the effective thermal conductivity in the first interval $v_s=[0\%, 30\%]$, while the decrease becomes smaller (0.3083 W/m/K) for the second interval ranging from 30%-60%.
3.3 Effect of the wall thickness of microsphere

To investigate the effect of the wall thickness of microsphere, the volume content of the microsphere keeps 30% unchanged and the values of thermal conductivity of the wall, gas and cement phases are also invariant, as tabulated in Table 1. When the wall thickness of the glass microsphere changes in the range \([0.25, 0.5, 1.0, 1.5, 2.0] \times 1.1095\mu m\), the corresponding equivalent thermal conductivity of the composite is presented in Fig. 7, from which it is shown that as the wall thickness of the glass microsphere increases, the equivalent thermal conductivity of the composite almost linearly decreases. The main reason is that the wall of microsphere is silicate and has
smaller thermal conductivity than that of the cement matrix. The thickness increase of the wall, which means volume increase of the wall, leads to the wall region occupy more volume of the cement.

### 3.4 Effect of the thermal conductivity of cement

The effect of thermal conductivity of the cement phase on the effective thermal conductivity of the composite here is studied. In the sensitivity analysis, the volume content of the microsphere is assumed to be 30%. The thermal conductivities of the wall and the gas keeps unchanged, as those values in Table 1, while the values of thermal conductivity of the cement are chosen to be \([0.25, 0.5, 1.0, 1.5, 2.0] \times 0.93 \, \text{W/(mK)}\), respectively. Fig. 8 displays the approximated linear change of the effective thermal conductivity of the composite with the increase of the thermal conductivity of the cement. As expected, the larger the thermal conductivity of the cement is, the larger the equivalent thermal conductivity of the composite is.

![Graph showing the effect of thermal conductivity of cement](image)

**Fig. 8.** Variation of the effective thermal conductivity of the composite to the thermal conductivity of the cement matrix

### 3.5 Effect of the thermal conductivity of wall

Finally, to estimate the effect of thermal conductivity of the wall, the value of microsphere volume content is still assumed to keep 30%, and the thermal conductivities of the cement and the gas are 0.93 \, \text{W/(mK)} and 0.0228 \, \text{W/(mK)}, respectively, as shown in Table 1. The values of the control parameter, the thermal conductivity of wall, are assumed to be changed in the interval \([0.25, 0.5, 1.0, 1.5, 2.0] \times 0.1793 \, \text{W/(mK)}\). Results in Fig. 9 show that the equivalent thermal conductivity of the composite shows slightly nonlinear increase with the increase of thermal conductivity of the wall.
4. Conclusions

The interest in developing and modeling macroscale cement-based composites filled with hollow glass microspheres has led to the use of micromechanical techniques to model the effect of microstructure of composites. Herein, the heat transfer behavior due to the present of hollow glass microsphere and the effects of some control parameters of the microstructure of the composite on its effective thermal conductivity are investigated. It's observed from the results that the change of the volume content of the microsphere causes significantly nonlinear change of the effective thermal conductivity of the composite. It's reasonable that the inner gas which has extremely low thermal conductivity occupies most of volume of the microsphere, thus the increase of the microsphere volume content necessarily causes the dramatic decrease of the entire thermal property of the composite. Besides, the thickness of the wall has negative effect on the effective property of the composite, while the thermal conductivities of the wall and the cement are observed to have positive effects on the effective property of the composite, as expected.

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References


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