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Numerical investigation of compressive behavior of cement matrix composites filled with hollow glass microspheres

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Abstract: Lightweight composite materials filled with hollow glass microspheres (HGMs) have been widely used as thermal insulation materials, due to the extremely small thermal conductivity of HGM which is mainly caused by enclosed gas pore. However, for extensive industrial applications, the compressive performance of composite material also needs to be considered. This work focuses on the numerical prediction of compressive properties of hollow glass microsphere filled cement matrix composites. The volume fraction of filler is changed from 5% to 20%. Under the applied compressive stress and displacement constraints, the representative unit cell is solved by finite element simulation to determine the normal strains in the compression and transverse directions. Then, the compressive modulus and Poisson ratio can be evaluated for assess the compressive properties of composites. The results can provide guidance to the design of cement-based composite filled with HGMs.

Keywords: Composite; Cement; Hollow glass microsphere; Compressive modulus; Poisson's ratio; Finite element

I. INTRODUCTION

Composites consisting of filler and matrix are common used in industrial production because they are lightweight, high strength, as well as many other advantages [1-5]. Among various fillers, i.e. circular or polygonal fibers [6-8], spherical or polyhedral particles [9], hollow glass microspheres (HGMs) consisting of inner inert gas and outer glass shell show lower density and thermal conductivity than the pure glass material [1]. Liu et.al investigated the thermal conductivity of HGM experimentally and numerically. They concluded that the thermal conductivity of HGM is about 0.13W/(mK), which is significantly smaller than that of glass [2]. Thus, HGMs are widely used to fabricate lightweight composites to provide better thermal insulation property [3-8]. For example, Liu et.al.developed a numerical three-dimensional model for predicting the thermal conductivity of HGM-filled cement matrix composite [9]. Besides, a simplified two-dimensional composite model was also established for studying the thermal behavior of composites filled with HGMs [10, 11]. For extensive industrial applications, i.e. deep-sea engineering, the compressive properties of HGM-filled composites should be considered as well. In this field, some researches have been conducted to reveal the relation of compressive properties of polymer matrix composites and the content of HGMs [7, 12-14], however, rare investigation involves the mechanical properties of cement matrix composites filled with HGMs.

In this paper, the effects of HGM content on the compressive properties of cement matrix composites are systematically investigated by finite element simulation, which is more flexible than theoretical and experimental methods to provide more detailed information of mechanical behavior of composites. The results can provide guidance for the potential applications of HGM-based cement composites.

II. NUMERICAL MODELLING

To model HGM-based cement composites, one has to build a simulation domain containing HGMs and cement matrix. Here, it is assumed that the HGMs disperse in the cement matrix in regular hexagonal arrangement. Then, the unit cell shown in Fig. 1a includes a centered HGM and eight 1/8 parts of HGM. Obviously, the density of the composite material will decrease as the content of HGM filled in cement matrix increases, for the reason that the density of HGM is typically lower than that of the cement matrix material. In the subsequent discussions, we define d=47.8μm to be the inner diameter of the HGM and t=1.1μm to be the thickness of the glass shell in the unit cell model [11]. Table 1 lists the elastic modulus and Poisson's ratio of glass and cement matrix material, which are estimated according to literature [24].

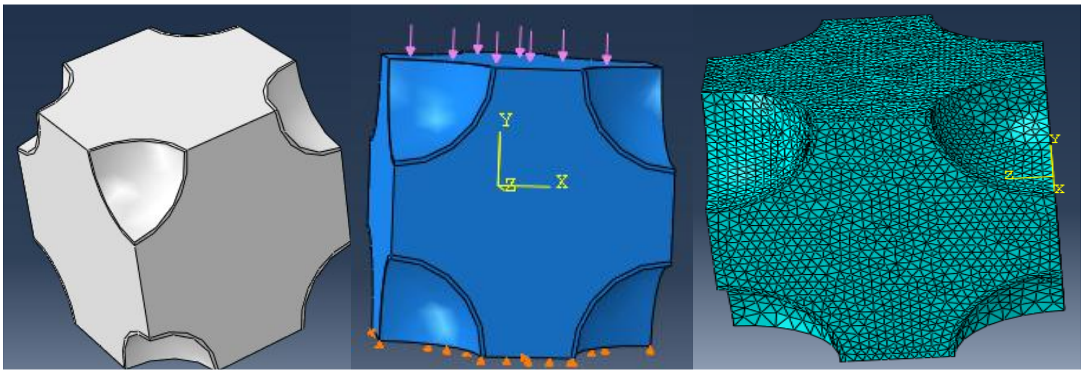
In the finite element simulation, the representative unit cell is solved under the applied boundary conditions. For example, as indicated in Fig. 1b, the top surface is loaded with a compressive stress 100Pa, and the bottom surface is fixed in the loading direction. The other surfaces keep free. The unit cell is discretized by quadratic tetrahedral elements, as displaced in Fig. 1c. For such a model, the effective elastic modulus of the unit cell can be calculated by [1]

$$E_c = \frac{\hat{\sigma}_y}{\hat{\varepsilon}_y} \quad (1)$$

where $\hat{\sigma}_y$ is the applied compressive stress in the *y*-direction on the top surface, and $\hat{\varepsilon}_y$ is the averaged normal strain in the *y*-direction at all nodes. Whilst, the Poisson's ratio of composite can be determined by

$$\nu_c = \left| \frac{\hat{\varepsilon}_x}{\hat{\varepsilon}_y} \right| \quad (2)$$

where $\hat{\varepsilon}_x$ is the averaged normal strain in the transverse *x*-direction at all nodes.



(a) (b) (c)

Fig. 1 The representative unit cell (a), the applied boundary conditions (b) and the mesh configuration (c)

Table 1 Mechanical properties of glass and cement material [15]

Material	Elastic modulus	Poisson's ratio
Glass	55GPa	0.25
Cement	26GPa	0.14

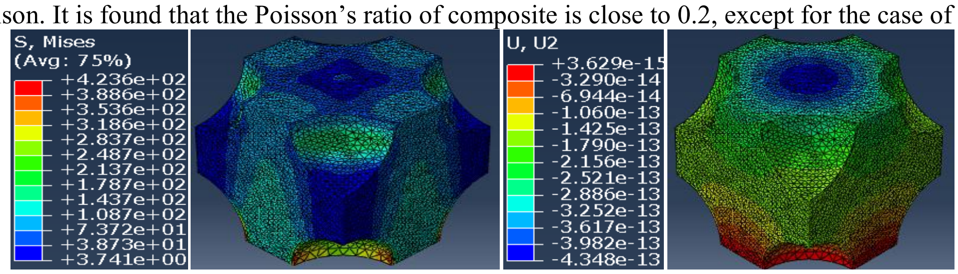
III. RESULTS AND DISCUSSIONS

In the finite element simulation, the volume fraction of HGM is assumed to be changed from 5% to 20%. Correspondingly, the side length of unit cell can be evaluated by

$$a = \sqrt[3]{\frac{8\pi R^3}{3v_f}}, \qquad (R = \frac{d+2t}{2}) \quad (3)$$

Next we take the unit cell model with 10% HGMs as an example to show the stress and displacement distribution in the compressed unit cell. Fig. 2a and 2b respectively display the variations of Von-Mises stress and displacement in the y-direction. It is observed from Fig. 2a that the existence of HGM makes the distribution of stress non-uniform. Also, as we expect, under the applied compressive stress, the unit cell becomes short in the compressive direction (see Fig. 2b).

The effect of volume fraction of HGM on the compressive properties of composites is then studied for different unit cell models. It is noted from Table 2 that the elastic modulus of composite changes in terms of HGM content. Its value almost linearly decreases from 24.88GPa to 18.18GPa as the volume fraction of HGM increases from 50% to 20%. The main reason is that the porosity of HGM is extremely high, thus more HGMs bring more voids in the cement matrix. Besides, the Poisson's ratio of composite is provided in Table 2 as well for comparison. It is found that the Poisson's ratio of composite is close to 0.2, except for the case of 5% HGM.



(a) (b)

Fig. 2 Distributions of Von-Mises stress (a) and displacement in the *y* direction (b) in the unit cell with 10% HGMs

Table 2 Compressive properties of composite against the HGM content

HGM content	5%	10%	15%	20%
Elastic modulus E_c	24.88GPa	22.57GPa	20.16GPa	18.18GPa
Poisson's ratio ν_c	0.156	0.207	0.194	0.210

IV. CONCLUSIONS

By utilizing finite element simulation, the compressive behaviors of HGM-filled cement matrix composites with changed HGM volume contents from 5% to 20%are investigatedin the paper. The representative unit cell is established based on the assumption of regular distribution of HGMs in the cement matrix, and then it is solved numerically to evaluate the compressive modulus and Poisson's ratio of composites. It is concluded that the increasing content of HGM in the cement matrix will lead to the remarkable declination of compressive modulus of composites. This is because more voids are introduced in the composite when the HGM content increases. Whilst, the Poisson's ratio is found to have slight change when the HGM content varies. Therefore, one can achieve desired compressive performance of HGM-filled composites by adjusting the content of HGMs. Such results can provide better guidance to engineering applications of HGMs.

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