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# Numerical study on the effect of pore shapes on the thermal behaviors of cellular concrete

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## HIGHLIGHTS

- A 2D model was used to investigate the effect of pore shapes on the ETC of cellular concrete.
- Representative volume elements of porous microstructures were reconstructed using a random algorithm.
- The results provide information on the microstructure-thermal property relationship for the cellular concrete.

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## ABSTRACT

This paper proposes a numerical method to study the effect of pore shapes on the effective thermal conductivity (ETC) of cellular concrete by a two-dimensional model. Cellular concrete can be seen as a composite of two phases with pore and cement paste. The model is established by two steps. Firstly, a generation of two-dimensional representative volume element of cellular concrete microstructure is necessary. Secondly, a finite element method is adopted to simulate heat transfer through the pixelated microstructure. Simulations are validated against analytical approximations, as well as experimental data from the literature. The model can also be used to evaluate the pore size distribution and orientation effects that are hard to measure only in laboratory experiments. It is concluded that ETC decreases when triangle pores substitute for circular pores on account that the tortuosity increases continuously. The other shapes of non-circular pores (square, pentagon and hexagon) have negligible effects on ETC. For ellipse cases, ETC decreases with increase in aspect ratio and volume fraction of pore. In the case of aligned pores, the ETC is larger along the principal axis. However, the size distribution of pores seems to have an insignificant influence. The numerical results suggest that the finite element method (FEM) considering quantitative data of thermal transfer behavior of cellular concrete can be obtained by the pore shapes, and it may be of great help to the optimization of materials.



## 1. Introduction

Recently in all sorts of engineering field, lightweight concrete gets more and more attention owing to its good thermal properties but with low weight, such as good thermal insulation properties regardless of the good fire resistance, impact energy absorption and outstanding vibration damping behaviors [1–3]. According to the methods of production, lightweight concrete can be normally classified into three types: a) Using lightweight aggregate with low density in place of the normal weight aggregate, which is named as lightweight aggregate concrete. b) Mixing bubbles together with the mortar matrix or cement paste, which is named as cellular concrete. c) Eliminating the fine aggregate while the coarse aggregate of ordinary weight is widely utilized, which is named as no-fines concrete. In order to improve the properties of lightweight concrete, it is important to derivate the relationship between the microstructure and its related performance, as the microstructure including porosity and pore shapes has a great influence on the performance of lightweight concrete [4].

The constitutive equation of porous materials between the microstructure and thermal behaviors either in an analytical or empirical way are proposed by many researchers in the literatures [5–7]. In all, there are two distinct ways which are in a wide use. The first is one of an analytical way. For instance, the Hashin and Shtrikman expressions give the most widely used upper and lower limits of the ETC for a two-phase system where circular phase is assumed to place in a continuous medium [5]. Landauer derives

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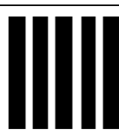
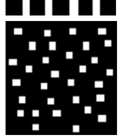
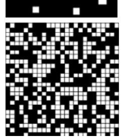
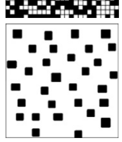
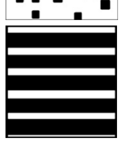
an analytical expression for a two-phase system where the connectivity of the phases is considered. This method is also called "Effective medium percolation theory" (EMPT). In five typical analytical models, the expressions are based on a simplified microstructure with the spatial distribution of the two phases, listed in Table 1. Although such ways usually offer a useful modification on the properties of porous materials, the real properties of porous materials are no expressed exactly. Since the microstructure of materials are complex and inhomogeneous and the oversimplified hypotheses about microstructure, materials with circular or elliptic isolated pores are suitable for these ways.

The second is derived from the numerical method which takes the geometric details of the pores into consideration [8–13]. R. Coqurad et al. calculate the effect thermal conductivity (ETC) of two-phase heterogeneous materials by this way. Wei et al. set up microstructure of cellular concrete by random generation method and an analogical resistor network method is used to solve the energy transport equations for fluid-solid coupled heat transfer. In the aforementioned theoretical researches, pores in matrix are seen as a two-dimensional circle or a three-dimensional sphere but the influence of pore shapes on the thermal characteristics of porous material are neglected. However, this issue is of great importance to create appropriate material structure for thermal insulation properties [14]. Hence, this numerical method combined with microscopic tests is rather practicable approach for predicting the thermal transfer behavior in cellular concrete with pore shapes effect. Although all the pores of cellular concrete are in three dimension and two dimensional simulation results are smaller than three dimensional simulation results due to three dimensional effect [15], the simulations in this paper are carried in two dimension for simplification, because many measurements used to characterize the microstructure of porous material (SEM, Microscope) are usual two dimensional.

Therefore, this study focuses on accurate quantification how morphological changes affect thermal properties of cellular concrete by FEM. The influence of pore shapes and porosity on thermal transfer properties of cellular concrete is studied by five types of pore shapes (circle, ellipse, square, pentagon and hexagon). Representative volume elements of porous microstructures are set up by an algorithm randomly and the tortuosity is calculated with a random walk method because many experimental results testified that tortuosity of transfer paths is linked with transfer behavior. The results offer relationship between the microstructure and thermal property of the cellular concrete and confirm the feasibility of FEM to enhance awareness and adjustment of porous microstructure for application.

**Table 1**
The five analytical effective thermal conductivity (ETC) models for two-phase systems.

| Model | Structure schematic | ETC equation |
|---|---|---|
| Parallel model |  | $k = k_1 v_1 + k_2 v_2$ |
| HS+ model |  | $k = k_1 + \frac{v_2}{1/(k_2 - k_1) + (v_1/3k_2)}$ |
| EMPT model |  | $v_1 \frac{k_1 - k}{k_1 + 2k} + v_2 \frac{k_2 - k}{k_2 + 2k} = 0$ |
| HS− model |  | $k = k_2 + \frac{v_1}{1/(k_1 - k_2) + (v_2/3k_1)}$ |
| Series model |  | $k = (\frac{v_1}{k_1} + \frac{v_2}{k_2})^{-1}$ |

## 2. Theoretical model of ETC

Firstly, theoretical parameters including circularity and aspect ratio are calculated for pores with different shapes. Then, shape factor is used to link the circular pores together with other shaped pores to predict the ETC of porous material. Due to the supposition that the area of the representative pore and the equivalent pore is the same with each other, the shape factor for a regular polygon can be calculated and compared to simulated results.

### *2.1. Theoretical parameters for pore shape*

Both geometrical and mathematical characterization of a pore in three dimension or a projective pore in two dimension need various parameters [16–18]. The most general definition to describe pore shape is listed as follows:

The circularity ($C$) is defined as the approximation degree of a pore to a circle by using the area ($A$) and the perimeter ($P$) ratio of the pore [19]:

$$C = \frac{4\pi A}{P^2} \tag{1}$$

The aspect ratio (AR) is another parameter used widely. This parameter takes the measurement along two axes into consideration and indicates the deformation of a pore well. However, no agreement is reached how to evaluate the measurement of different dimension of irregular shapes. For an ellipse, the aspect ratio usually donates the ratio of the major axis to the minor axis, and the results are in values of AR $\geqslant 1$. Some authors used reciprocal AR (1/AR) as an elongation (E) value, however, the definition proposed by Kröner is used [20]:

$$E = 1 - \frac{1}{AR} \tag{2}$$

While AR value ranges from 1 to infinite, the elongation calculated in this method changes from 0 to 1 as circularity. For a $n$-sided regular polygon, the calculation of the area is as follows:

$$A = \frac{P^2}{4n\tan(\pi/n)} \tag{3}$$

where $n$ represents the number of sides of the polygon.

### *2.2. Theoretical model of ETC considering the pore shape factor*

There have been many attempts at predicting the ETC of two phases conducting mixture taking the pore shape factor into consideration. According to Bauer, a particular solution to the Laplace heat transfer equation is derived by disturbing the initial uniform temperature distribution in the continuous medium due to the presence of pores [21]. The corresponding change in the ETC of the two phase medium is calculated by solving the following equation, as

$$\frac{dk_e}{k_e} = -\frac{1 - k_f/k_e}{2/3\beta + (1 - 2/3\beta)k_f/k_e}\frac{dV}{V} \tag{4}$$

where $k_f$ is the thermal conductivity of the pores, $k_e$ is the ETC of the porous material associated with the total volume of pores $V$, and $\beta$ is