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Theoretical and computational modeling of clustering effect on effective thermal conductivity of cement composites filled with natural hemp fibers

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Abstract

This paper investigates the effects of clustering on the effective transverse thermal conductivity of unidirectional cement composites filled with natural hemp fibers. A typical clustering pattern with four hemp fibers embedded into cement matrix is designed as the representative two-dimensional unit cell, which is taken from the periodic cement composite under consideration, and a clustering degree parameter is introduced to adjust the distance between clustered fibers. For this heterogeneous two-component composite model, distributions of the heat flux component are obtained using finite element simulation for various clustering cases involving different global fiber volume concentrations, clustering degree parameters, and thermal conductivity of both fiber and matrix, to evaluate the effective thermal conductivity of the composite. To further reveal the effects caused by clustered fibers, a random cluster pattern of hemp fibers in the unit cell is considered for comparison with the present regular clustering pattern. Further, a simple theoretical model with specified flexible factor *f* is developed by matching the theoretical and numerical predictions.

Keywords

Cement composites, hemp fiber, clustering, thermal conductivity, finite element method

Introduction

Cement is the most common material for buildings, paths, and driveways. Challenges are to produce environmentally friendly construction products of cement that are structurally safe and durable. In the search for advanced green biocomposites, much attention has been attracted to the use of natural fibers in cement matrix, due to their unique advantages such as low cost, low density, low thermal conduction, high specific strength, and nonabrasive, ecofriendly, and biodegradable nature.[1–9] More importantly, with their inherent hollow microstructure, natural fibers can exhibit much lower thermal properties than artificial fibers such as carbon fiber and glass fiber, and thus they can be used as thermal insulators of building materials to improve building energy efficiency. The study of the overall thermal conductivity of natural fiber-filled cement composites has thus become a hot topic in civil engineering.

Micromechanical models have been continuously developed over the past two decades for predicting the overall thermal conductivity of natural fiber-filled composites.[10–14] This was done by considering the thermal properties of matrix and natural fiber and their respective volume fractions, under the assumption of uniform distribution of natural fibers. It has been noted, however, that existing methods were unsatisfactory for accurately predicting the material properties of composites where the reinforcement distribution is not

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uniform. Clustering of reinforcements, for example, may occur on a smaller scale during composite processing for reasons such as chemical reaction, physical property difference, or insufficient mixture.[15,16] As such, the interaction of clustered reinforcements is unavoidable and can affect efficient load transfer from matrix to reinforcements, thereby affecting the overall properties of composites. For example, Segurado et al. investigated the clustering effect of spherical reinforcements on the mechanical behavior of metal matrix composites by numerically solving three-dimensional multiparticle cubic unit cells.[17] Later, similar clustering problems in sphere-reinforced ductile-matrix composites were analyzed by Segurado and Llorca through finite element simulation.[18] Abedini et al. numerically studied the role of spherical particle clustering in the macroscopic and microscopic behavior of particle-reinforced composites by considering different arrangements of clustered particles as well as different cluster densities.[19] Wang and Qin investigated the influence of randomly dispersed fibers on the thermal behavior of fiber-reinforced composites by specially purposed elements.[20] Qin and Swain developed a micromechanics model for predicting effective properties of dentin composites.[21] Trias et al. compared two-dimensional random and periodic models in fiber-reinforced composites and concluded that the random model was suitable for local phenomena.[22] Sihn and Roy conducted parametric study on transverse thermal conductivity of laminated composites for both analytic and numerical models with regular and randomly distributed fibers in matrix material.[23] The effects of interaction among randomly dispersed holes or cracks, which could be viewed as fibers with null material properties, on the thermal or elastic behavior of composites were studied using specially purposed elements.[24–26] As well, analysis of clustered materials filled with nanotubes has been performed using the tessellation method in conjunction with a multiphase Mori–Tanaka technique[27] and the finite element method (FEM).[28] These clustering models have provided valuable insight into the clustering effect of particle or artificial fiber reinforcements. To the best of our knowledge, however, few studies have rigorously investigated the clustering effect of natural fibers on the effective thermal conductivity of cement composites. It is necessary to incorporate such effects for prediction of the effective thermal properties of composites filled with natural fibers.

The aim of this study is to establish a theoretical and computational model of cement composites with clustered hemp fibers for predicting the effective thermal conductivity of composites and identifying the dominant parameters that can control effective thermal conductivity. In the clustered composites under consideration, these parameters usually include: (1) clustering degree of the regular cluster, (2) global fiber volume concentration, (3) fiber and matrix thermal conductivity, and (4) random clustered arrangement. The results will enhance understanding of clustering behavior in cement composites filled with natural hemp fibers and will provide guidance in the design of novel composites.

The paper is organized as follows. In "Micromechanical model of clustered composites" section, the micromechanical cell model of clustered cement composites is presented. "Theoretical model" section establishes a theoretical composite model with flexible factor. "Finite element model" section provides the finite element analysis of clustered composites through representative cell approach. "Results and discussion" section presents numerically the effective thermal conductivity of the composite by accounting for the degree of clustering, global fiber volume concentration, fiber thermal conductivity, and random clustered arrangement, and the flexible factor is also determined. Finally, some conclusions are drawn in the final section.

Micromechanical model of clustered composites

The microstructure of periodically unidirectional cement composite materials with clustered natural hemp fibers is shown in Figure 1(a), in which the square packing mode of fibers is employed. According to the periodicity of clustered fibers, a representative unit cell can be isolated from the composite, having the same thermal properties and fiber volume concentration as the composite under consideration, as illustrated in Figure 1(b). Moreover, homogenization of the representative cell leads to an equivalent orthotropic homogeneous medium as shown in Figure 1(c), with certain effective thermal conductivities that

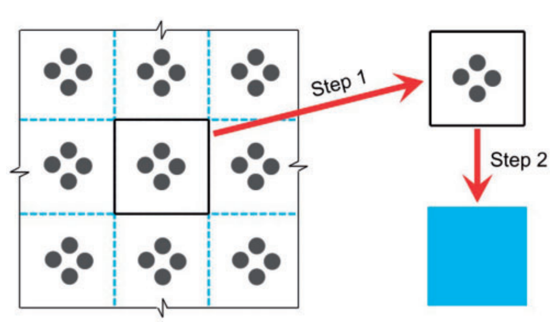


Figure 1. A two-step homogenized procedure for the periodic composite with natural clustered hemp fibers. (a) Composited with clustered fibers, (b) unit cell, and (c) equivalent homogenized medium.

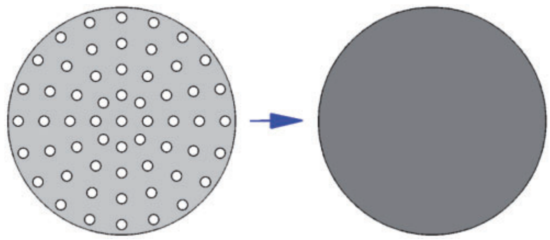


Figure 2. Schematic view of cross-section of cellulous hemp fiber (left) and the equivalent solid fiber (right).

describe the average material properties of the composite.

The SEM image of the cross-section of Manila hemp fiber shows large numbers of lumens within it, and thus it is a typical cellulous structure.[13,29] Both theoretical results from the Hasselman–Johnson's model and numerical results by finite element analysis have shown that the effective thermal conductivity of the hemp fiber is 0.115 W/(m K),[13,30] so the practical hemp fiber in this study is modeled as an equivalent isotropic homogeneous solid circular fiber with thermal conductivity $k_f = 0.115\,\mathrm{W/(m\ K)}$ and diameter equal to the outer diameter of the hemp fiber, as shown in Figure 2. Here, the value of the fiber diameter is taken as 200 μm.[11,12] Additionally, it is assumed that the cement matrix phase is isotropic and homogeneous and has thermal conductivity $k_m = 0.53\,\mathrm{W/(m\ K)}$.[31] Moreover, to make the microstructure model mathematically tractable, it is assumed that the hemp fibers and the cement matrix are perfectly bonded so that no interfacial thermal contact resistance exists between them.

Under the above assumptions, the steady-state local temperature fields in the matrix and the fiber, denoted by T_m and T_f, should satisfy following Laplace governing equations, respectively[32]

$$\frac{\partial^2 T_m}{\partial x_1^2} + \frac{\partial^2 T_m}{\partial x_2^2} = 0, \quad \frac{\partial^2 T_f}{\partial x_1^2} + \frac{\partial^2 T_f}{\partial x_2^2} = 0 \tag{1}$$

and the continuous conditions at the interface between the hemp fiber and the matrix are

$$\begin{aligned} T_m &= T_f \\ k_m \frac{\partial T_m}{\partial n} &= k_f \frac{\partial T_f}{\partial n} \end{aligned} \tag{2}$$

where x_1 and x_2 in the above formula refer to the coordinate axial directions, and n is the unit direction normal to the fiber/matrix interface.

To quantitatively investigate the clustering effect of hemp fibers in the composite, the cluster pattern shown in Figure 3 is taken into consideration. In Figure 3, the four hemp fibers are, respectively, arranged along the four different directions within the cement matrix to generate a clustering effect, and a parameter λ is introduced to control the degree of clustering by adjusting the distance between hemp fibers. L denotes the side length of the square cell and R the radius of the hemp fiber. The specified boundary conditions are shown in Figure 3, which has been successfully employed by many researchers to predict the effective transverse thermal conductivity of unidirectional fiber-reinforced composites.[13,20,24,33] The applied temperature constraints are assumed as $T_1 > T_2$ so that the thermal currency flows through the cell from left to right and the heat fluxes along the horizontal direction applied over the two side surfaces are equal and are kept positive.

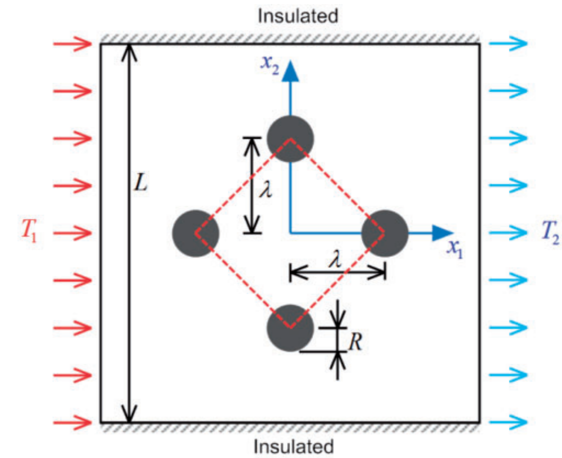


Figure 3. Representative unit cell and boundary conditions for the clustered composite.

As expected, it is observed that the axial thermal property of the clustered unidirectional composite is unaffected by clustering. As such, only the results for transverse thermal conductivity are provided. Based on Fourier's law of heat transfer in orthotropic media,[32] we have the following relationship of the temperature variable T and the heat flux component q_i

$$q_i = -k_i \frac{\partial T}{\partial x_i} \quad (i = 1, 2) \tag{3}$$

from which the effective thermal conductivity k_i^{eff} of the homogenized medium shown in Figure 1(c) can be evaluated by

$$k_i^{eff} = -\frac{\bar{q}_i}{\bar{\varepsilon}_i} \quad (i = 1, 2) \tag{4}$$

In equation (4), $\bar{q}_i$ is the area-averaged heat flux component along the x_i-direction on a given cross-section perpendicular to the x_i-axis and $\bar{\varepsilon}_i$ is the temperature gradient along this direction. Due to the heterogeneous nature of the composite, the heat flux component q_i is not uniform over the given cross-section perpendicular to the x_i-axis. However, it was systematically verified that the area-averaged heat flux component $\bar{q}_i$ was the same at any cross-section perpendicular to the x_i-axis. In this work, for the imposed temperature difference along the x_1-direction, as shown in Figure 3, the area-averaged heat flux component $\bar{q}_1$ over the right surface denoted as AB can be computed by the integral

$$\bar{q}_1 = \frac{1}{L}\int_{AB} q_1(x_1, x_2)\mathrm{d}x_2 \tag{5}$$

and the temperature gradient component along the x_1-direction is given by

$$\bar{\varepsilon}_1 = \frac{(T_2 - T_1)}{L} \tag{6}$$

Theoretical model

Several theoretical models are currently available for predicting the effective thermal conductivity in heterogeneous multicomponent composites. The most straightforward of these theoretical models are series and parallel models. Yet they can only give the lower and upper bounds of the effective thermal conductivity of composites rather than accurate results. In this study, a more general theoretical model developed by Kirkpatrick[34] is extended to the present case and used to predict the effective thermal conductivity of the considered two-component composites containing the hemp fiber phase and the cement matrix. The model can be formulated as

$$v_m \frac{k_m - k_1^{eff}}{k_m + \left(\frac{f}{2} - 1\right)k_1^{eff}} + v_{fc}\frac{k_f - k_1^{eff}}{k_f + \left(\frac{f}{2} - 1\right)k_1^{eff}} = 0 \tag{7}$$

in which f is a flexible factor associated with the actual microstructures of the composites and v_m and v_{fc} are volume concentrations of matrix and fiber, respectively. Typically, the flexible model in equation (7) can reduce to the effective medium theory (EMT) model[35] by simply setting $f = 6$, that is

$$v_m \frac{k_m - k_1^{eff}}{k_m + 2k_1^{eff}} + v_{fc}\frac{k_f - k_1^{eff}}{k_f + 2k_1^{eff}} = 0 \tag{8}$$

Further, equation (7) can be rewritten to obtain the explicit expression of k_1^{eff} as

$$k_1^{eff} = \frac{1}{f-2}\left\{\left(\frac{f}{2}v_m - 1\right)k_m + \left(\frac{f}{2}v_{fc} - 1\right)k_f + \sqrt{\left[(\frac{f}{2}v_m - 1)k_m + (\frac{f}{2}v_{fc} - 1)k_f\right]^2 + 2(f-2)k_m k_f}\right\} \tag{9}$$

In equation (9), determination of the flexible factor f with respect to a particular heterogeneous composite medium usually requires physical experiments or numerical modeling. In the present study, numerical prediction is performed using the FEM,[36,37] and then the criterion with the smallest Euclidean normal of the residual of the theoretical and numerical predictions

$$\min ||\mathbf{t}||_2 = \min\sqrt{\sum_{i=1}^{m}\left(s_i^{theoretical} - s_i^{numerical}\right)^2} \tag{10}$$

is employed to determine the optimal value of f. In equation (10), $s_i^{theoretical}$ and $s_i^{numerical}$, respectively, denote the theoretical and numerical predictions of the effective thermal conductivity at i^{th} point. m is the number of sampling points.

Finite element model

From ‘‘Micromechanical model of clustered composites’’ section, it can be seen that three parameters control the effective material properties in the representative unit cell: (1) the global volume concentration v_{fc} of the clustered fibers to the cell, (2) the parameter λ describing clustering degree, and (3) the fiber and matrix thermal conductivities. In practical computation, the desired volume concentrations can be achieved either by adjusting the fiber radius R while holding the unit cell length L constant or by adjusting the unit cell length L and holding the relevant radius R constant, and the results have no evident discrepancy.[38] Here, we employ the latter method to produce the desired global volume concentrations and the relevant geometrical size of the unit cell can be evaluated by any specified value of the fiber volume concentration v_{fc}, that is

$$L = R\sqrt{\frac{p\pi}{v_{fc}}} \tag{11}$$

where p is the number of hemp fibers in the cluster in the unit cell. Typically, for $p = 4$ and $R = 100\,\mu\text{m}$, the induced side length L of the unit cell is presented in Table 1 for reference.

Table 1. Relation of global fiber volume concentration to cell length.

v_{fc}	5%	10%	15%	20%	25%	30%
L (μm)	1585.3	1121	915.3	792.7	709	647.2

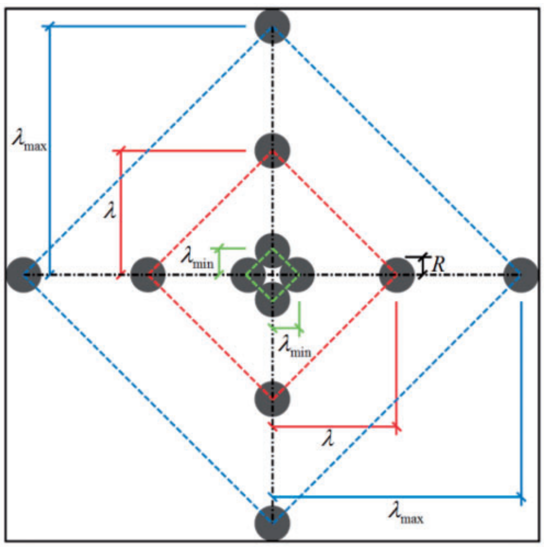


Figure 4. Schematic of minimum and maximum values of the parameter λ.

Additionally, the choice of the parameter λ is constrained by the cell size. Figure 4 provides two special cases for the parameter λ. It can be found that the minimum theoretical value of λ can be determined by

$$\lambda_{\min} = \sqrt{2}R \tag{12}$$

while the maximum theoretical value of λ can be evaluated by

$$\frac{\lambda_{\max}}{R} = \frac{1}{2}\sqrt{\frac{p\pi}{v_{fc}}} - 1 \tag{13}$$

For example, if $p = 4$ and $v_{fc} = 10\%$, the minimum and maximum values of λ/R are, respectively, 1.41 and 4.60, and if $p = 4$ and $v_{fc} = 30\%$, the maximum value of λ/R drops to 2.24 while the minimum value is unchanged.

Once the micromechanical cell model of the composite is established, the thermal response of the composite can be obtained by finite element analysis of the unit cell. The simulation in this study was carried out with ABAQUS/Standard and the model volume (matrix and clustered fibers) was meshed using eight-node quadratic heat transfer quadrilateral elements (DC2D8 in ABAQUS). Approximately 548 elements were used to represent each fiber, ensuring that the geometrically approximating error in the discretized circular domain was within 0.01% of the theoretical value. Moreover, the discretization of the unit cell was required to be fine enough to yield accurate and convergent results, which were defined such that the maximum relative difference in the predicted local averaged heat flux was less than 0.01% when the mesh size was reduced.

Further, to validate the computational tool, a unit cell containing a fiber was simulated with the same boundary conditions as those given in Figure 3 but assuming $k_m = k_f = 0.53\,\mathrm{W/(m\ K)}$. As expected, the predicted area-averaged heat flux at the right face of the cell fell within 0.000032% of the theoretical value given by the Fourier law

$$q_1^{\text{theoretical}} = -k_m \frac{T_2 - T_1}{L} \tag{14}$$

for $L = 323.6\ \mu$m, $R = 100\ \mu$m, $T_1 = 20°$C, and $T_2 = 0°$C.

Results and discussion

Effect of volume concentration of single fiber

To draw comparisons between the results obtained for the well-dispersed hemp fibers and the clustered hemp fibers, the representative cell including a single hemp fiber is first taken into consideration for the well-dispersed case. Figures 5 and 6, respectively, display the variations of the heat flux component over the right surface of the cell and the effective thermal conductivity k_1^{eff} along the x_1-direction of the composite for various fiber volume concentrations. From Figure 5, it is obvious that the heat flux is not uniform over the chosen data collection surface because of the heterogeneous nature of the composite. Moreover, the nonuniformity increases as the fiber volume concentration increases. Figure 6 shows the effective thermal conductivity k_1^{eff} of the composite containing single hemp fiber as a function of fiber volume concentrations ranging from 5 to 30%. Because the fiber thermal conductivity $k_f = 0.115\,\mathrm{W/(m\ K)}$ is much less than the matrix thermal conductivity $k_m = 0.53\,\mathrm{W/(m\ K)}$, the effective thermal conductivity k_1^{eff} decreases as v_{fc} increases, as expected, and this decrease shows slight nonlinearity.

To validate the present model, the obtained results were compared with available those from experiments,[12] which was for composites with polymer matrix. The influence of different matrix materials such as the cement matrix and the polymer matrix on the effective thermal conductivity of composites is discussed here. The thermal conductivity of the polymer

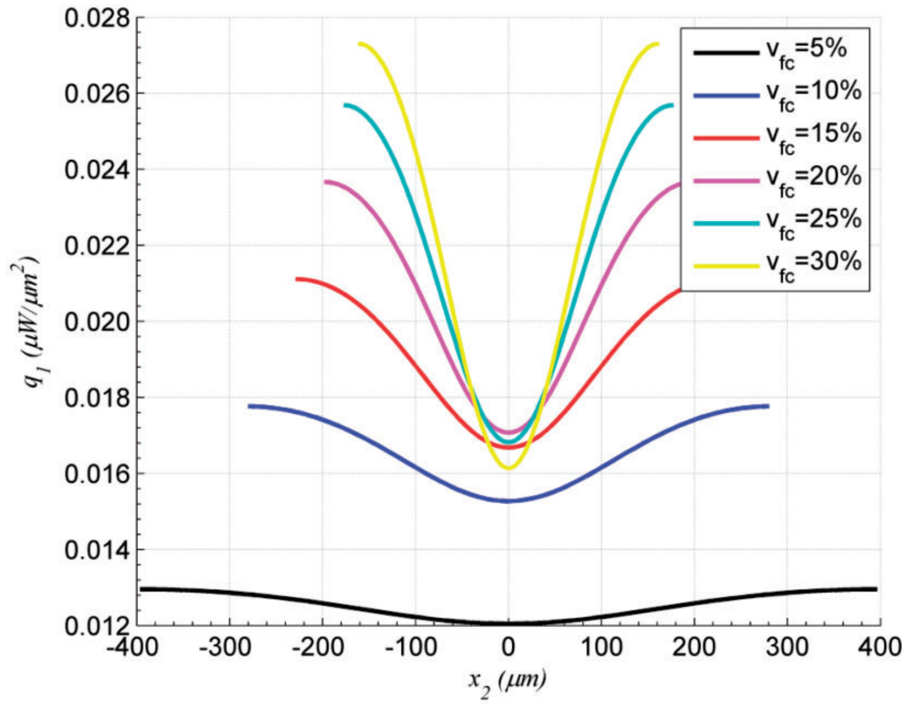


Figure 5. Distribution of heat flux component on the right surface of the cell for the well-dispersed case.

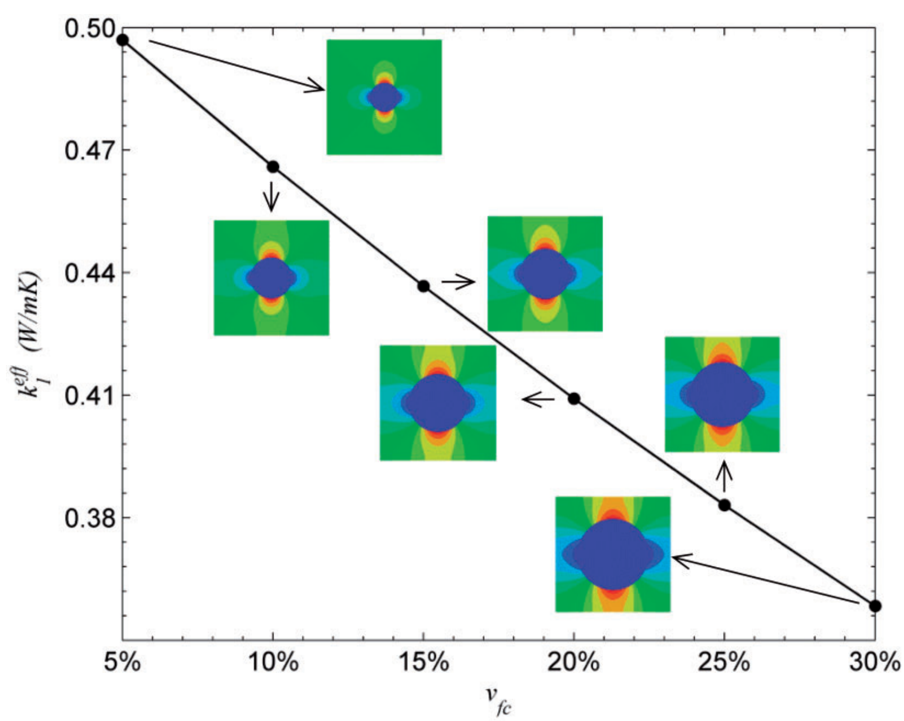


Figure 6. Variation of effective thermal conductivity of the composite for the well-dispersed case.

matrix is 0.42 W/(m K).[12] In Table 2, transverse composite thermal conductivities are compared between numerical and experimental results for 50 and 60% fiber volume concentrations, respectively. It is found that the cement matrix can produce higher effective thermal conductivity of composite than the polymer matrix at same fiber volume concentration, as expected. This is due to the fact that the cement matrix has lager thermal conductivity than the polymer matrix. Besides, it is observed that the thermal conductivity of composite from FEM is little bit lower than that from experiments. The main reason might be that the experimental data are measured with some random orientated hemp fibers in the polymer matrix (see Figure 3(a) in Behzad and Sain[12] for detail).

Effect of volume concentration of the clustering fibers

For the clustered case, the effect of volume concentration of the clustered fibers on the effective thermal conductivity of the composite is first studied by simply setting the clustering degree $\lambda/R = 2$. The global fiber volume concentration is assumed to range from 5 to 30%.

Figures 7 and 8, respectively, present the effects of clustering on the heat flux and the effective thermal conductivity for a range of global fiber volume concentrations. It is found from Figure 7 that the heat flux on the right surface of the cell shows similar uniformity to that in Figure 5, which corresponds to a single fiber only. However, there is a large deviation in their quantities for the same fiber volume concentration. It is further observed from Figures 5 and 7 that the associated cell lengths L are also different for the same fiber volume concentration in the well-dispersed and clustered cases. Subsequently, the corresponding temperature gradients obtained from equation (6) are also different for the two cases. Regarding the overall thermal property of the composite, Figure 8 demonstrates that, in general, there is a decreasing effect of clustering on the effective thermal conductivity of the composite with the increase of fiber volume concentration for the values of k_f and k_m considered. Compared to the well-dispersed case (no cluster), the clustered case seems to produce similar curves of effective thermal conductivity. This can be attributed to the negative and positive changes of the averaged heat flux and the cell length. To rigorously indicate the difference between the results from the well-dispersed and clustered cases, the results of averaged heat flux, cell length, and effective thermal conductivity for the two cases are presented in Table 3 for comparison. From Table 3, it can be seen that the cell length in the well-dispersed case is half that in the clustered case, whereas the averaged heat flux in the well-dispersed case is approximately twice that of the clustered case. As a

Table 2. Comparison of composite thermal conductivity between numerical and experimental results (unit: W/(mK)).

v_{fc}	50%	60%
Cement matrix	0.2705	0.2311
Polymer matrix	0.2328	0.2038
Experiment[12]	0.2757	0.2296

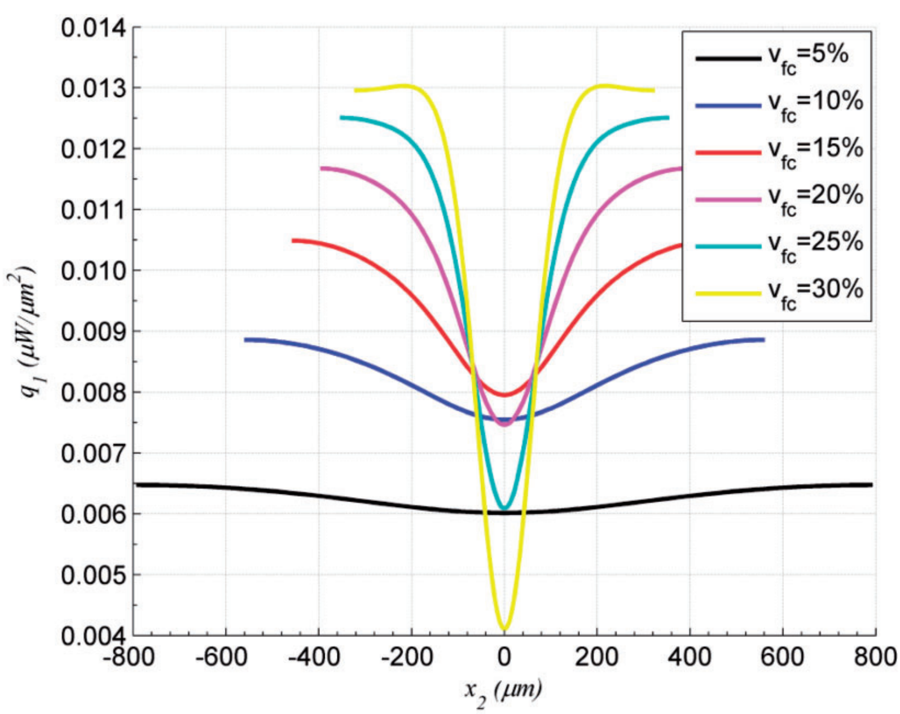


Figure 7. Distribution of heat flux component on the right surface of the cell for various clustered fiber volume concentrations.

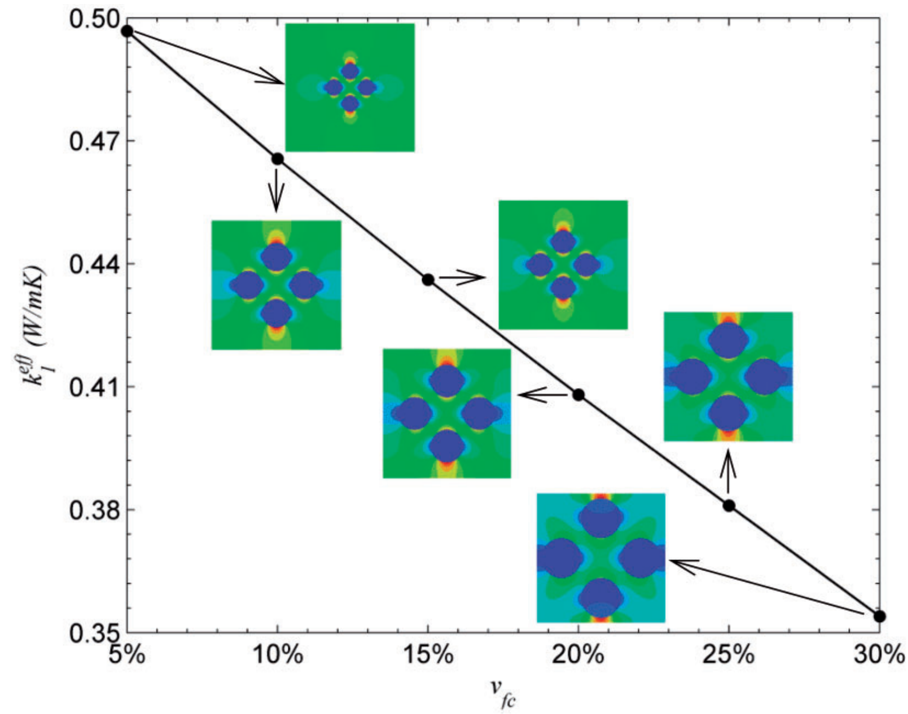


Figure 8. Variation of effective thermal conductivity of the composite for various clustered fiber volume concentrations.

Table 3. Comparison of well-dispersed and clustered cases.

v_{fc}	5%	10%	15%	20%	25%	30%
Well-dispersed case						
L (μm)	792.67	560.50	457.65	396.33	354.49	323.60
$\bar{q}_1$ $\left(\frac{\mu W}{\mu m^2}\right)$	0.01254	0.01663	0.01908	0.02065	0.02161	0.02215
k_1^{eff} $\left(\frac{W}{mK}\right)$	0.49696	0.46592	0.43670	0.40913	0.38306	0.35835
Clustered case						
L (μm)	1585.33	1121.00	915.29	792.67	708.98	647.21
$\bar{q}_1$ $\left(\frac{\mu W}{\mu m^2}\right)$	0.00627	0.00831	0.00953	0.01030	0.01074	0.01094
k_1^{eff} $\left(\frac{W}{mK}\right)$	0.49681	0.46559	0.43610	0.40806	0.38103	0.35399

result, the induced effective thermal conductivities of the composite are almost the same for both cases.

The FEM predictions and the theoretical model predictions are plotted in Figure 9 for comparison. It is clearly seen that the EMT model ($f = 6$) produces a large difference from the FEM predictions, whereas the flexible model gives good overall agreement with the FEM predictions if the flexible factor f is taken to be 4.5, which corresponds to the smaller residual square normal between the FEM and the theoretical predictions. Thus, the theoretical flexible model with $f = 4.5$ can be used to approximately predict the effective thermal conductivity of the cement-based composite filled with hemp fibers considered in this study.

Effect of degree of fiber clustering

The effect of degree of clustering on the distribution of the heat flux along the chosen surface of the cell and the effective thermal conductivity of the composite is quantitatively investigated in this subsection. From equation (13), it is obvious that the maximum value of the parameter λ/R is in terms of the fiber volume concentration v_{fc}. Therefore, we take $v_{fc} = 10\%$ so that the values

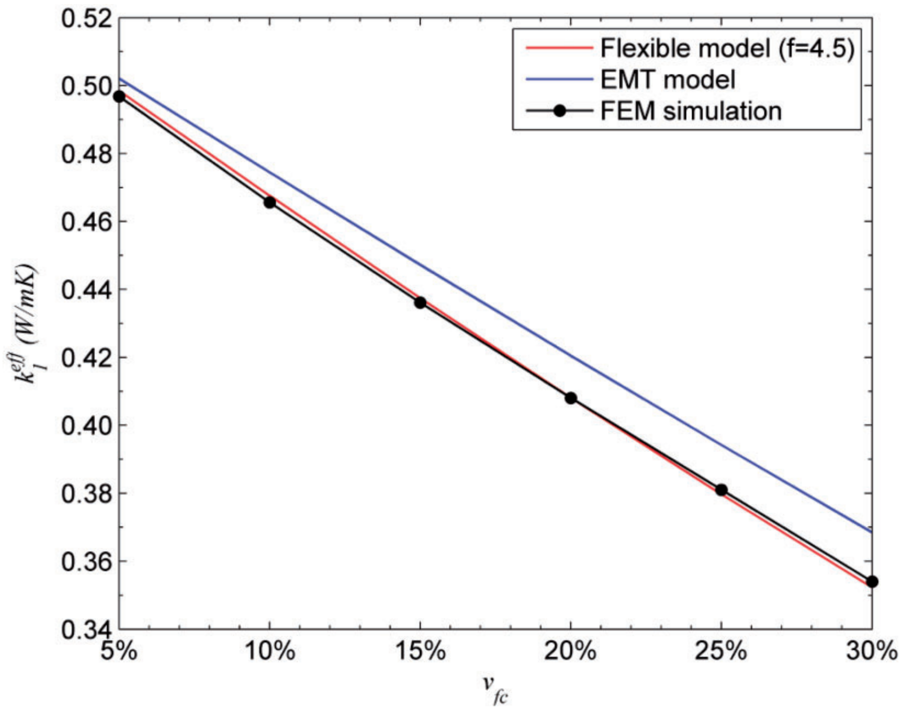


Figure 9. Comparison of effective thermal conductivity of the composite between the FEM predictions and theoretical predictions.

of the parameter λ/R can change over a large range of [1.5, 4.5]. Here, the minimum value 1.5 of λ/R corresponds to the most clustered case and the maximum value 4.5 corresponds to the least degree of clustering. It is necessary to note that for such cases the temperature gradient is kept unchanged, so that the induced effective thermal conductivity of the composite dependents on the averaged heat flux only.

Figures 10 and 11, respectively, indicate the changes in the heat flux component over the right surface of the cell and the effective thermal conductivity of the composite for different cluster arrangements controlled by the ratio λ/R. It is obvious that although the heat flux curve becomes steeper as the ratio λ/R increases, no change in its averaged value is evident. The ratio of the maximum and minimum values of the effective thermal conductivity is just 1.0037. Thus, it can be concluded that changes in the degree of clustering affects only the local heat flux field in the cell, whereas the overall thermal conductivity of the composite is not sensitive to the degree of clustering in the microstructure.

Effect of random distribution of fiber clusters

Unlike the regular clustering mode, the random mode of fiber clustering is likely to be more practical in the fabrication of composites. Here, two random cluster modes of fibers are taken into consideration for the global fiber volume concentration $v_{fc} = 10\%$ and $k_m = 0.53\,\mathrm{W/(m\ K)}$, $k_f = 0.115\,\mathrm{W/(m\ K)}$. It should be noted that the cell size is kept constant during this test, so that the temperature gradient in the cell is also kept unchanged. Thus, the overall thermal property of the composite is associated only with the average heat flux. Random distribution of the fiber clusters can be generated by setting different distances from the fiber center to the centroid of the unit cell. Figure 12 plots the variation of heat flux over the right surface of the cell. It is obvious from Figure 12 that the change of random cluster mode greatly affects the heat flux distribution on the right surface of the cell. However, it seems that such a change in the random cluster mode does not significantly affect the average value of the heat flux. Table 4 provides comparisons between the two random cluster modes, the regular cluster mode, and the single fiber mode. Only small discrepancies are found among all the modes in the effective thermal conductivity.

Effect of fiber thermal conductivity

In this subsection, the sensitivity of the thermal property of the fiber material is investigated to demonstrate the effect of difference in fiber material on the composite. In the analysis, the global fiber volume

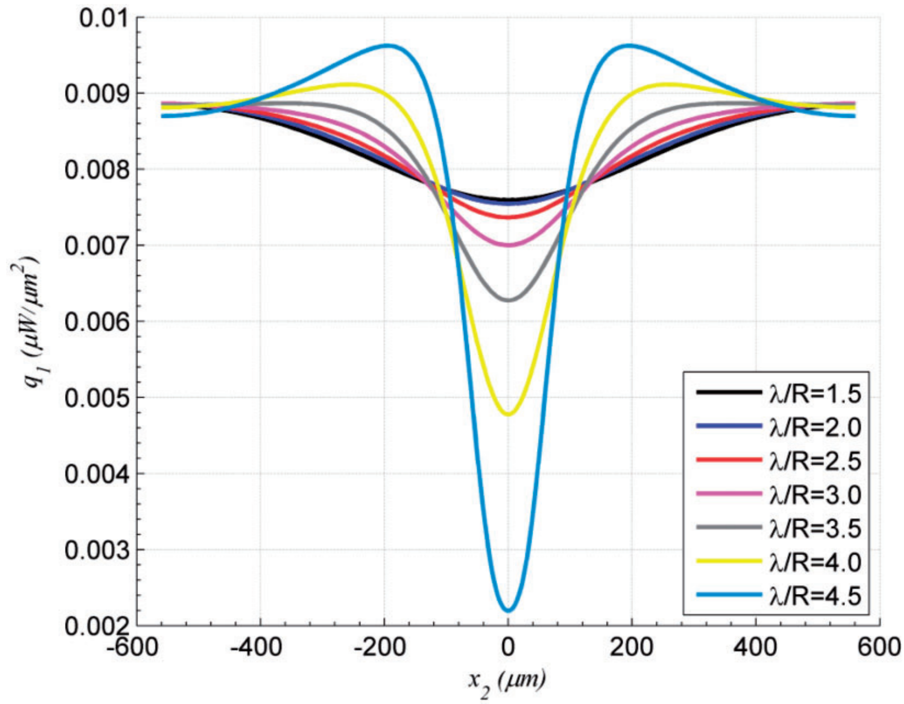


Figure 10. Distribution of heat flux component on the right surface of the cell for various degrees of clustering.

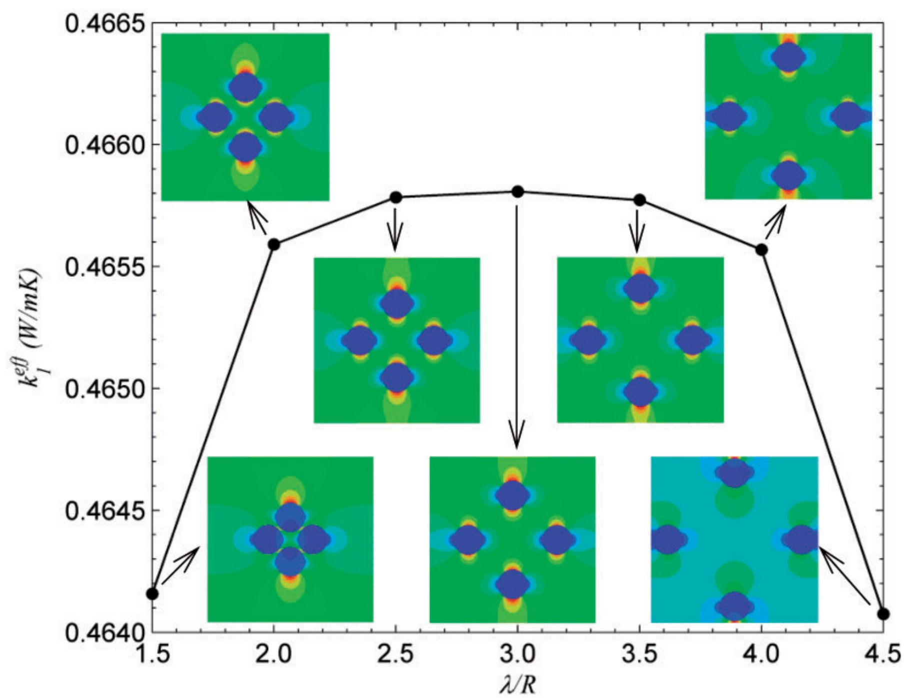


Figure 11. Variation of effective thermal conductivity of the composite for various degrees of clustering.

concentration is chosen as 10% and the degree of clustering is $\lambda/R = 2$. The thermal conductivity of the fiber is assumed to change from one-fourth (0.02875 W/(m K)) to six times (0.69 W/(m K)) that of the hemp fiber.

Figure 13 plots the effective thermal conductivity of the composite material in terms of fiber thermal conductivity. It is found that k_1^{eff} increases as k_f increases. The explanation is that the increase in the fiber thermal

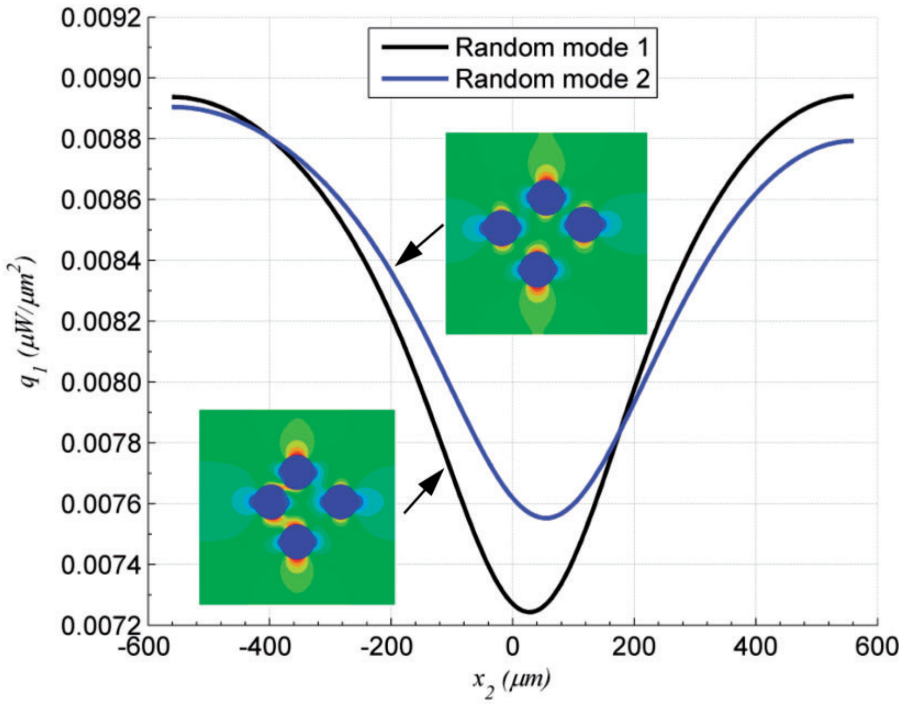
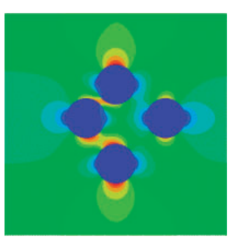
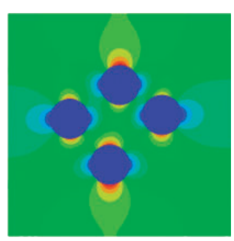
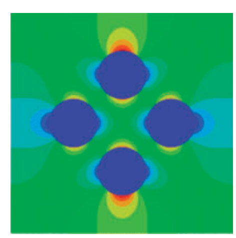
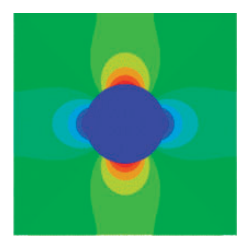


Figure 12. Distribution of heat flux component on the right surface of the cell for two randomly clustered cases.

Table 4. Comparison between various cluster modes.

	Randomly clustered mode 1	Randomly clustered mode 2	Regular clustered mode ($\lambda/R = 2$)	Single fiber mode
Contour map				
k_1^{eff} W/(mK)	0.4646	0.4670	0.4656	0.4659

conductivity k_f permits more heat to flow through the fiber. In this case, the route of heat transfer in the composite becomes short and complex, leading to the increase in the heat transfer property of the composite.

Conclusions

Rigorous prediction of the influence of the hemp fiber cluster on the effective transverse thermal conductivity of unidirectional two-component composite materials containing cement matrix and hemp fiber phase was performed by finite element simulation and theoretical analysis. The results obtained show that, despite the large contrast between heat flux distributions caused by different degrees of clustering and distributions of random fiber clustering, the overall thermal conductivity of the composite was basically independent of fiber cluster distribution. The overall thermal conductivity was dominantly determined by the fiber volume concentration and the fiber/matrix thermal conductivity. The similar conclusion was found for spherical particle-reinforced composites in the elastic regime.[17,18] Moreover, the theoretical flexible model with flexible factor $f = 4.5$ was found to give predictions that were consistent with

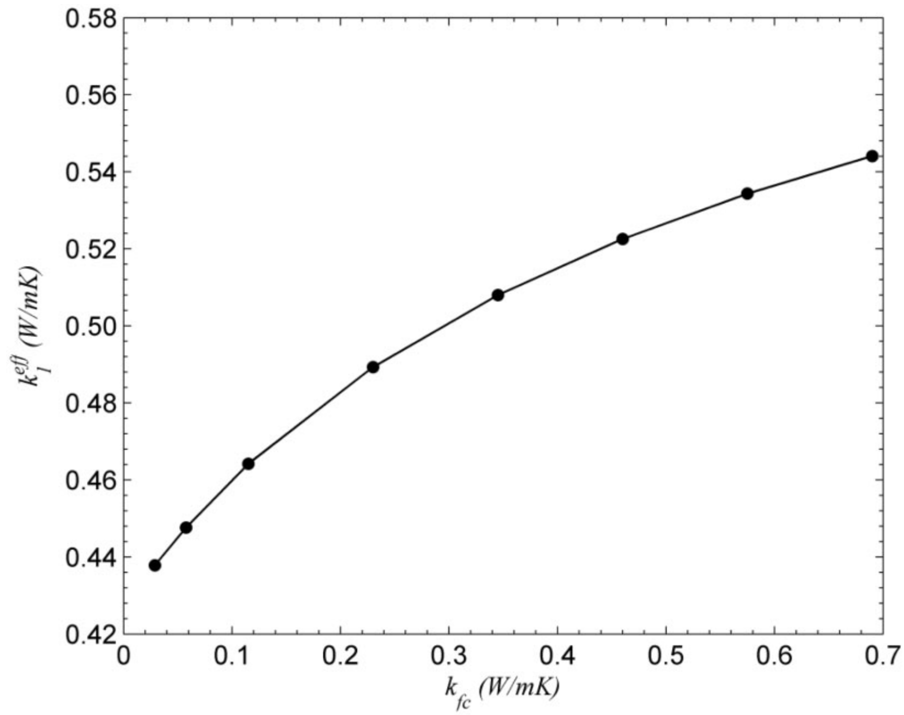


Figure 13. Variation of effective thermal conductivity of the composite for various thermal conductivities of the matrix phase.

numerical predictions using the FEM. Thus, the theoretical model can be used for the development of cement-based composites filled with hemp fibers.

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Conflict of Interest

None declared.

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