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Modeling thermal conductivity of hemp insulation material: A multi-scale homogenization approach

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ABSTRACT

The growing awareness of environment protection and climate change have increased the attention on the development of new environmentally-friendly materials. This study will concentrate on the thermal performance of hemp shives which are used as insulation material. A multi-scale homogenization approach accounting for the shape and orientation of pores and particles is developed to model the effective thermal conductivity and anisotropy of this bio-based material. An inverse analysis using the experimental thermal conductivity data of dry shives in bulk allows determining the thermal conductivity of the solid phase of hemp shiv, which is difficult to measure. The latter is then used in the multi-scale model to estimate the overall thermal conductivity of a single hemp shiv particle and hemp insulation material as functions of the temperature and moisture content. The effect of hemp shiv particle's size on the effective thermal conductivity and its anisotropy will be also discussed.

1. Introduction

According to the studies of United Nations Environment Program (UNEP) and the International Energy Agency (IEA), it is estimated that at present, buildings contribute as much as one third of total global greenhouse gas emissions, primarily through the use of fossil fuels during their operational phase [11,29]. In France, the building sector which is considered as one of major contributors to carbon emissions, accounted for 44% of total energy consumption in 2012. This energy consumption can be reduced significantly by renovating the insulation for existing buildings and respecting the system insulation rules for new buildings. The most commonly used thermal insulation materials are produced either from minerals or from petro-chemical-based raw materials. However, high embodied energy which presents the quantity of energy hidden in these raw materials will increase the building's operational energy demand. Due to the growing awareness of environment protection and climate change, there has been increasing attention focused on the development of new environmentally-friendly materials such as bio-based materials. Various bio-based insulations made from hemp shives [10,23], straw-clay [8], flax shives [10,15], diss [2], rap straw [16] can be used. Among these bio-based materials, hemp insulations are considered as new materials in the field of insulation which is more and more recommended by the eco-builders. Therefore, this study will concentrate on the use of hemp shives as insulation material when sandwiched between the roof/wall membranes. This choice is based on its quality merits, including environmental quality [23]. This material exhibits excellent acoustic and hygrothermal properties which can reduce the heat diffusion (saving of heating energy in building) and maintain indoor hygrothermal comfort thanks to its moisture buffering capacity [3–5,9,19]. Furthermore, the emissions of bacteria and VOCs (volatile organic compounds) are negligible [14]. In addition, regarding the annual production of hemp shives (granular of hemp descended from the inner woody core), France is one of the most relevant cultivation countries. The literature reviews showed that outside of the thermal conductivity of hemp shives in bulk which has been measured by some authors [28,30], limited information is available on the thermal performance of hemp insulation in relation to its density, its particles' orientation and moisture content. Homogenization-based model could be used to take into account these parameters [17,18,20,24–26]. Therefore, the present paper

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Nomenclature

$\underline{q}$	local heat flux vector
$\underline{\mathcal{Q}}$	overall heat flux vector
T	temperature
$\underline{\nabla T}$	temperature gradient
$\underline{E}$	overall temperature gradient
λ	thermal conductivity
$\boldsymbol{\lambda}$	thermal conductivity tensor
γ	thermal conductivity anisotropy
S	saturation degree
X	aspect ratio of the inclusion
Q	anisotropic parameters of the inclusion
f	volume fraction of a phase
φ	porosity
φ_{inter}	porosity between the particles
φ_{hp}	porosity of a particle
c	dimensionless conductivity
$\boldsymbol{I}$	second order unit tensor
$\boldsymbol{A}$	second order localization tensor
$\boldsymbol{P}$	second order Hill's tensor

Subscript

m	index stands for the matrix phase
inc	index stands for the inclusions
hp	index or superscript stands for hemp shiv particle
h	index or superscript stands for hemp shives in bulk
s	index stands for the solid phase
w	index stands for water
a	index stands for air
hom	superscript stands for homogeneous properties
T	index stands for transversal component of the transversely isotropic tensors
N	index stands for normal component of the transversely isotropic tensors
$\bar{a}$	overbar stand for the volume average of a value a

aims to provide analytical solutions for the effective thermal conductivity and anisotropy of these bio-based insulation materials. First, the theoretical basis of the homogenization approach is presented. A multi-scale homogenization scheme is then developed accounting for the shape and orientation of the pores and particles. An inverse analysis, using the experimental thermal conductivity data of dry shives in bulk, yields the thermal conductivity of the solid phase of hemp shiv particle. This parameter is anew used in the multi-scale model to predict the overall thermal conductivity of hemp shive particle, hemp shives in bulk as function of the temperature and moisture content. Finally, the effect of shive particle size on the effective thermal conductivity and its anisotropy are studied in detail.

2. Theoretical basis

The overall conductivity of heterogeneous media can be obtained by considering the relationship between the local and the macroscopic behavior of a Representative Elementary Volume (REV) (the size of REV must be very large comparing with the local size of the pores and particles and must be very small comparing with that of the structure) that are resumed by the following equations:

$$\underline{q}(\underline{z}) = -\boldsymbol{\lambda}(\underline{z})\underline{\nabla T}(\underline{z}) \tag{1}$$

$$\underline{\mathcal{Q}} = -\lambda^{\text{hom}}\underline{E} \tag{2}$$

$$\underline{\mathcal{Q}} = \frac{1}{|\Omega|}\int_{\Omega}\underline{q}(\underline{z})d\Omega \tag{3}$$

$$\underline{E} = \frac{1}{|\Omega|}\int_{\Omega}\underline{\nabla T}(\underline{z})d\Omega \tag{4}$$

where $\underline{q}(\underline{z})$, $\underline{\nabla T}(\underline{z})$ and $\lambda(\underline{z})$ are the local heat flux vector, the local thermal gradient field and the local conductivity tensor at point $\underline{z}$ inside the REV, respectively; $\underline{\mathcal{Q}}$, $\underline{E}$ and λ^{hom} are the overall heat flux vector, thermal gradient field and conductivity tensor of the REV, respectively; Ω the REV and $|\Omega|$ its volume. The local and the average thermal gradient field tensors are related by the following linear equation:

$$\underline{\nabla T}(\underline{z}) = \boldsymbol{A}(\underline{z})\underline{E} \tag{5}$$

where $\boldsymbol{A}(\underline{z})$ is the localization tensor at point $\underline{z}$. The combination of Equations (1) to (5) yields the following equation to calculate the overall conductivity tensor of the REV:

$$\lambda^{hom} = \frac{1}{|\Omega|}\int_{\Omega}\lambda(\underline{z})\boldsymbol{A}(\underline{z})d\Omega \tag{6}$$

In Equation (6), the local conductivity tensor $\lambda(\underline{z})$ is assumed to be known, the main question is to determine the localization tensor $\boldsymbol{A}(\underline{z})$. The extension of the [12], of a single ellipsoidal inclusion in an infinite homogeneous matrix (Fig. 1a), for transport property provides an analytical solution of $\boldsymbol{A}$, noted by $\boldsymbol{A}^*$ that takes the form:

$$\boldsymbol{A}^* = (\boldsymbol{I} + \boldsymbol{P}(\boldsymbol{\lambda}_{inc} - \boldsymbol{\lambda}_m))^{-1} \tag{7}$$

where λ_{inc} and λ_m are the conductivity tensors of the inclusion and of the matrix reference, respectively, $\boldsymbol{I}$ the second order unit tensor. The second order tensor $\boldsymbol{P}$ is the Hill tensor [22], that depends both on the shape of the inclusion and the conductivity of the reference matrix.

The solution (7) can be extended for the general case of multi-inclusions (Fig. 1b) by manipulating the boundary condition to take into account the interaction between the inclusions [13,27].

$$\boldsymbol{A} = \boldsymbol{A}^*\overline{\boldsymbol{A}^*}^{-1} \tag{8}$$

where $\bar{a}$ stands for the average over the whole domain of a value a: $\bar{a} = \frac{1}{|\Omega|}\int_{\Omega} a d\Omega$.

The combination of Equations (6)–(8) yields:

$$\lambda^{hom} = \overline{\lambda(\boldsymbol{I} + \boldsymbol{P}(\lambda - \lambda_m))^{-1}}\,\overline{(\boldsymbol{I} + \boldsymbol{P}(\lambda - \lambda_m))^{-1}}^{-1} \tag{9}$$

or