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Analytical and Experimental Investigations on the Heat Transfer Properties of Light Concrete[1]

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It is well known that the thermal performance of some insulating and building materials is related to the actual operating conditions because the thermal conductivity of such materials is highly dependent on the moisture content. Since the thermal conductivity of liquid water is about 25 times greater than that of air, it is quite easy to understand how even small variations of the moisture content can have a significant impact on thermal performance. For this reason it is important to find a correlation between the moisture content in a specimen and its thermal conductivity. The purpose of this paper is to investigate both experimentally and theoretically the moisture contribution during the measurement of the heat transfer properties in light concrete slabs (autoclaved concrete and concrete lighted with polystyrene pearls) and to correlate its thermal transmissivity with the moisture content.

KEY WORDS: heat transfer; light concrete; moisture transfer; thermal conductivity; vapor.

1. INTRODUCTION

A lot of experimental and research work has been done in these last years to characterize the behavior of insulating materials. Some insulating materials do not absorb water and their properties do not change, while there are other building materials, such as light concrete materials, whose properties are strictly correlated with their moisture content. The behavior of these semitransparent materials containing also water in the cells has

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been investigated, and a simple model to correlate the moisture content with the thermal transmissivity has been developed.

A theoretical analysis of the heat and mass transfer process for such a material was performed, and then a suitable numerical model was used to predict and analyze the moisture contribution to the thermal conductivity.

2. THEORETICAL MODEL

The behavior of homogeneous insulating materials containing air in the cells or among the fibers is well known [1–4]. Any modeling of heat transfer in insulating materials must obviously consider the three elementary processes of radiation, conduction, and convection. In most semitransparent cellular materials, conduction through the gas enclosed in the cells and radiation play a dominant role in the overall heat transfer process; conduction through the solid matrix is just a small fraction of the total heat transfer, while thermal convection can be neglected, due to the small size of the cells.

A semitransparent insulating material containing moisture may be treated as a multiphase system, with the voids of the solid skeleton partly filled with a gaseous mixture of dry air and water vapor whose behavior is represented by a mixture of ideal gases and partly filled with liquid water.

For this reason, the total heat flow density q is given by the following contributions due to the different components that are present in the material; see Fig. 1:

q_{cd} = heat flow density due to the thermal conduction in the solid matrix and in the gas (usually moist air) inside the pores of the material,

q_{w} = heat flow density due to the thermal conduction in the water inside the solid matrix walls,

q_{r} = heat flow density due to thermal radiation, and

q_{conv} = heat flow density due to thermal convection.

With regard to the first component q_{cd}, it is possible to express it by introducing the equivalent conductivity λ_{cd} using Fourier's law:

$$q_{cd} = -\lambda_{cd}\, \nabla T \tag{1}$$

The term q_{w} represents the heat flow density due to the conduction of the liquid water inside the solid matrix. As suggested in the literature [5, 6] and in the ISO Standards [7], this contribution is considered by adding the term aw to the thermal conductivity of the dry material (i.e., dried in oven

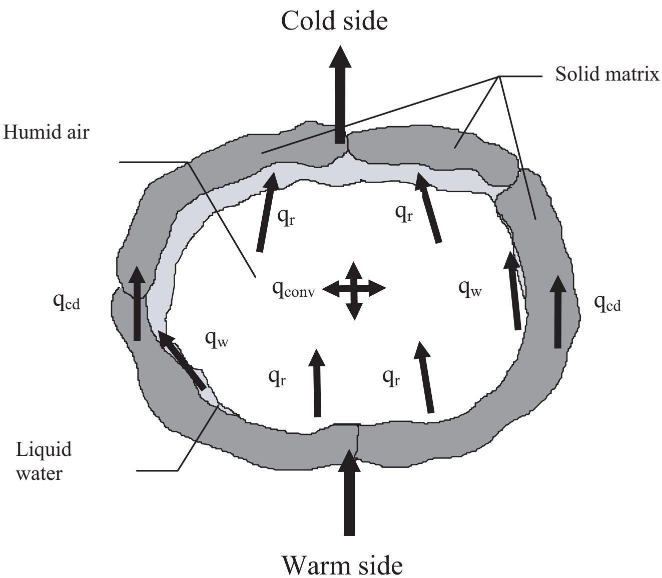

Fig. 1. Schematic diagram of the heat transfer mechanism inside a cellular moist material.

at 105°C) λ_{cd}, where a is a coefficient that represents the increase of the thermal conductivity due to the moisture content w of the material. The moisture content w is expressed as the ratio between the total amount of the moisture in the material and the volume.

It is possible to use the following expression to describe the complete contribution of conduction heat transfer in a moist insulating material:

$$q_{cd} + q_{w} = -(\lambda_{cd} + aw)\,\nabla T = -\lambda_{c}^{*}\,\nabla T = q_{c} \tag{2}$$

where the term $\lambda_{c}^{*} = \lambda_{cd} + aw$ represents the equivalent thermal conductivity of the moist material.

The behavior of the insulating materials may be accurately described if they are considered as an homogeneous semitransparent medium where combined conduction and radiation take place. The simplified model that we used is the model of Arduini and De Ponte [8] and is an application of the so called "two flux model" that was improved to describe better the examined material. If the material is considered optically thick, it is possible to express the heat flow density due to radiation q_{r} in the following way:

$$q_{r} = -\frac{8\sigma_{n}T_{m}^{3}}{S'\rho}\,\nabla T = -\lambda_{r}^{*}\,\nabla T \tag{3}$$

where S' is the extinction parameter of the moist material, ρ is the bulk density of the material, T_m is the mean test temperature, σ_n is the Stefan–Boltzmann constant, and λ_r^* is the hygrothermal radiativity. With regard to the last component of the heat flow density q_{conv}, it may be considered essentially negligible.

Thus, it is possible to describe the total heat flow density with the following expression:

$$q = q_c + q_r = -(\lambda_{cd}^* + aw + \lambda_r^*)\, \nabla T = -\lambda_t^*\, \nabla T \tag{4}$$

where the term λ_t^* is defined as the thermal transmissivity of the moist material. λ_t^* may be considered equal to the transfer factor $\mathscr{T}$ measured on a moist specimen whose thickness is sufficiently large to neglect the thickness effect, whose moisture content is uniformly distributed, and for which the macroscopic mass transport can be neglected.

The thermal transmissivity λ_t^* is therefore expressed as the sum of two terms: the first λ_c^* due to conduction heat transfer (both in the solid matrix of the material and in the gas) and the second λ_r^* due to radiation heat transfer:

$$\lambda_t^* = \lambda_c^* + \lambda_r^* \tag{5}$$

The first term λ_c^*, for a cellular material, depends on its bulk density ρ, and in high porosity materials, may be expressed as follows:

$$\lambda_c^* = \lambda_g (1 + B'\rho) + a^* w \tag{6}$$

where λ_g is the thermal conductivity of the gas enclosed in the cells, B' is a parameter depending on the geometry of the material, ρ is the bulk density of the material, a^* is a coefficient that accounts for the influence of moisture, and w is the moisture content in the material.

The parameter B' should remain within two limiting values according to the distribution of the material (all concentrated either in the struts or in the walls of the cells [9]).

For materials with a moderate porosity, λ_c^* may be expressed also as a function of the porosity of the material:

$$\lambda_c^* = \alpha[\xi\lambda_g + (1-\xi)\, \lambda_s] + (1-\alpha)\, \frac{\lambda_g \lambda_s}{\xi\lambda_s + (1-\xi)\, \lambda_g} + a^* w \tag{7}$$

where ξ is the porosity of the material (the ratio between the voids volume and the total volume), λ_g is the thermal conductivity of the gaseous phase, λ_s is the thermal conductivity of the solid matrix, and α is the fraction (in volume) of the solid structure components that are considered to be in parallel with the heat flow direction.

3. EXPERIMENTAL WORK AND VALIDATION OF MODEL

According to the model in the previous section, the thermal performance of autoclaved concrete and of light concrete (concrete lightened with polystyrene pearls) has been simulated in any working condition using Eqs. (5), (7), and (3).

The thermal transmissivity λ_t^* depends on the following parameters:

1. λ_g, the thermal conductivity of the gaseous phase whose temperature dependence has been evaluated with the following expression: $\lambda_g = \lambda_{air}(1+0.0030520\theta - 1.282\times 10^{-6}\theta^2)$ where λ_{air} represents the thermal conductivity of the air at 0°C and θ is the mean test temperature in °C,
2. w, the mean moisture content in the material,
3. λ_s^*, the thermal conductivity of the solid matrix,
4. a^*, the coefficient that accounts for the influence of the moisture content,
5. S', the extinction parameter due to combined absorption and scattering. This parameter is weakly temperature-dependent. A first-order approximation was introduced: $S' = S'_0(1+TCO\theta)$, where S'_0 is the value at 0°C and TCO is the temperature coefficient,
6. ξ, the porosity of the material,
7. α, the fraction (in volume) of the solid structure components that is considered to be in parallel with the heat flow direction.

Using Eqs. (5), (7), and (3), a least-squares analysis was applied for the best fit of the experimental data sets and to fully identify the basic parameters characterizing moist porous materials: λ_s^*, a^*, S', and TCO. The other aforementioned parameters were directly estimated from literature values.

The experimental data were obtained from a series of experimental measurements of the thermal transmissivity carried out on autoclaved concrete slabs and on slabs of concrete lightened with polystyrene pearls, with the heat flow meter method.

The specimens were slabs about 100 mm thick, to avoid the thickness effect [10]; the autoclaved concrete had a bulk dry density of 477 $kg\cdot m^{-3}$, while the light concrete had a bulk dry density of 458 $kg\cdot m^{-3}$.

These specimens were previously conditioned in a climatic chamber at 20°C, at three different relative humidities, respectively, 35, 50, and 80%. After each conditioning process, once hygrothermal equilibrium was attained, the specimens have been sealed in an impermeable envelope and the "moist" thermal transmissivity λ_t^* has been measured at a mean test temperature of 20°C and at three different temperature differences between the cold and hot sides, respectively, of 5, 10, and 20°C.

No significant change in the heat transfer factor $\mathscr{T}$ versus the proposed temperature difference was detected; this observation confirms that mass transport influence on the heat transfer may be neglected and that the measured transfer factor $\mathscr{T}$ may represent the thermal transmissivity λ_t^* of the moist material at a given moisture content.

After each set of measurements in the heat flow meter apparatus, the specimens have been dried in a ventilated oven at 105°C and then were again sealed in an impermeable envelope; their "dry" transfer factor $\mathscr{T}$ was measured at three different mean test temperatures of 10, 20, and 35°C with a fixed temperature difference of 20°C between the cold and hot sides.

All the experimental data, referred to the dry material (moisture condition $w = 0$), has been used in the least-squares analysis. The least-squares analysis applied to the measured transfer factor $\mathscr{T}$ of the autoclaved concrete and of the light concrete, showed that the mean square deviation is less than 0.5% (exactly 0.49% for autoclaved concrete and 0.29% for light concrete). The values of the parameters characterizing the thermal performance of the tested materials are summarized in Table I.

From the values of Table I and using Eqs. (3), (7), and (5), it is possible to deduce that the contribution of the thermal radiation to the total heat transfer in the autoclaved and in light concrete is only a few percent.

In Figs. 2 and 3 are presented the values of the thermal transmissivity of both materials, measured and calculated by using the best fit parameters obtained by means of the numerical regression. From an analysis of Figs. 2 and 3, it should be noted that the difference between experimental and calculated data is always less than 0.5%.

Table I. Parameters Characterizing the Thermal Performance of the Tested Materials

Parameter	Autoclaved concrete	Light concrete
λ^* ($W \cdot m^{-1} \cdot K^{-1}$)	1.1	0.98
a^* ($W \cdot m^2 \cdot kg^{-1} \cdot K^{-1}$)	4.70×10^{-4}	10.32×10^{-4}
S' ($m^2 \cdot kg^{-1}$)	7.55	7.57
TCO ($m^2 \cdot kg^{-1} \cdot °C^{-1}$)	1.7×10^{-4}	1.6×10^{-4}
α [−]	0.3	0.35

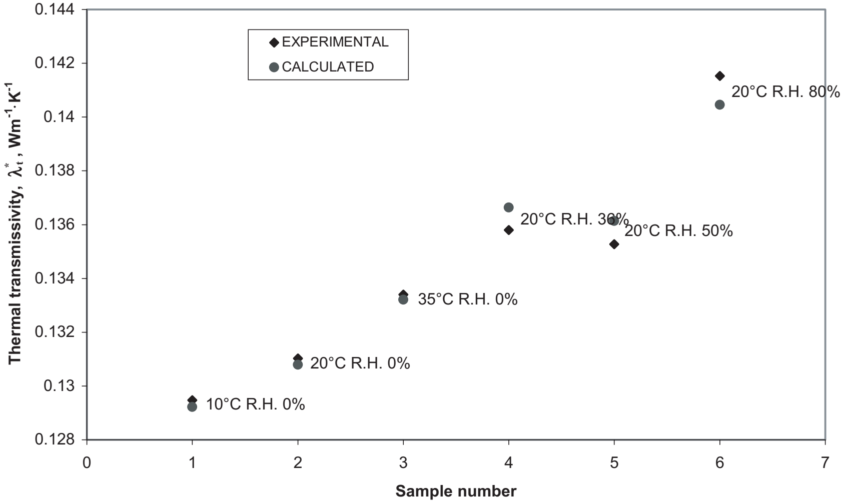

Fig. 2. Comparison between experimental and calculated data at different mean test temperatures and relative humidity R.H. for autoclaved concrete.

The present proposed approach to characterize the heat transfer performance inside porous materials with moderate porosity may be then usefully applied to evaluate the properties of the total heat transfer of composite materials such as autoclaved concrete and concrete lightened by means of polystyrene pearls.

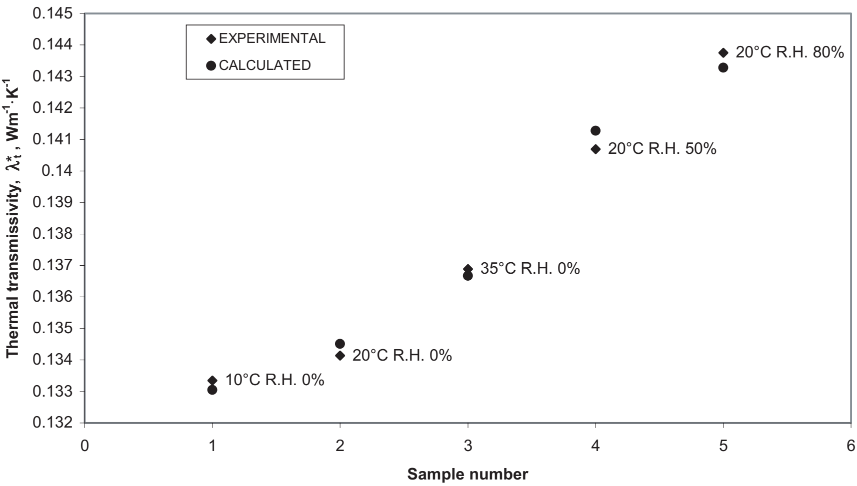

Fig. 3. Comparison between experimental and calculated data at different mean test temperatures and relative humidity R.H. for lighted concrete.

4. CONCLUSIONS

In this paper a simplified model has been proposed for estimation of the properties characterizing the conductive and radiative heat transfer in porous media with moderate porosity. An analysis of the thermal transmissivity of specimens of building materials such as autoclaved concrete and concrete lightened with polystyrene pearls at different mean temperatures and moisture content shows that the model can be fitted with the experimental data to within 0.5%.

The heat transfer properties estimated by means of the least-squares regression on the set of experimental measurements over wide ranges of temperature and moisture content can be used to identify the thermal performance of tested specimens with good accuracy.

Therefore, this approach avoids the need for experimental measurements at all conditions whenever numerical values of the thermal transmissivity of porous materials at selected temperatures and moisture content are required.

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