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Discerning heat transfer in building materials

N. C. Balaji[a]*, Monto Mani[b], B. V. Venkatarama Reddy[c]

[a]*Research Scholar, Centre for Sustainable Technologies, Indian Institute of Science, Bangalore 560012, India*
[b]*Associate professor, Centre for Sustainable Technologies, Indian Institute of Science, Bangalore 560012, India*
[c]*Professor, Department of Civil Engineering, Indian Institute of Science , Bangalore 560012, India*

Abstract

The function of a building is to ensure safety and thermal comfort for healthy living conditions. Buildings primarily comprise an envelope, which acts as an interface separating the external environment from the indoors environment. The building envelope is primarily responsible for regulating indoor thermal comfort in response to external climatic conditions. It usually comprises a configuration of building materials to thus far provide requisite structural performance. However, studies into building-envelope configurations to provide a particular thermal performance are limited. As the building envelope is exposed to the external environment there will be heat and moisture transfer to the indoor environment through it. The overall phenomenon of heat and moisture transfer depends on the microstructure and configuration within the building material. Further, thermal property of a material is generally dependent on its microstructure, which comprises a network of pores and particles arranged in a definite structure. Thermal behaviour of a building material thus depends on the thermal conductivities of the solid particles, pore micro-structure and its constituent fluid (air and/or moisture). The thermal response of a building envelope is determined by the thermal characteristics of the individual building materials and its configuration. Understanding the heat transfer influenced by the complex networks of pores and particles is a relatively new study in the area of building climatic-response. The current study reviews the heat-transfer mechanisms that determine the thermal performance of a building material attributed to its micro-structure. A theoretical basis for the same is being evolved and its relevance in regulating heat-transfer through building envelopes, walls in particular, is reviewed in this paper.

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Keywords: Heat Transfer; Building Envelope; Pore Structure; Thermal Conductivity; Thermal Performance

* Corresponding author. Tel.: +91-988-650-4699.
E-mail address: balajinallaval@gmail.com

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1. Introduction

The main function of a building is to ensure safety and thermal comfort for healthy working and living conditions for its inhabitants. This can be achieved through a proper climate responsive design of building. Climate responsive design is one in which the form, structure and material integration regulate occupants indoor thermal comfort in response to external climatic conditions. Climate responsive design is based on the way a building form and structure moderates the climate for human good and well-being [1]. Building comprises several envelopes elements (such as wall, roof, floor etc…) termed as "a surface or interface that separates external environment from the interior occupied space". It is an assemblage of several individual building materials.

Building envelope exposed to the external environmental conditions such as temperature (due to solar radiation and air temperature), air velocity (due to convection) and moisture content in air (humidity). Heat and mass transfer would occur through the envelope, generally from the outside environment to the inside environment. In this work only heat transfer is considered. Heat transfer through a building envelope can be attributed to a combination of conductive, convective and radiative heat transfer components determined by the constituent material and its microstructure. This controls the material thermophysical properties such as thermal conductivity, specific heat and density. A detailed study towards the thermal characteristics of individual materials/elements is necessary for better understand the thermal behaviour of building envelope. Fig. 1 provides an overview into the thermal-performance of a typical building envelope.

The design of the building materials for a required thermal performance is of critical importance [1], which depends on the constituent material and microstructure. In the current study, an attempt is being made to understand and characterize the thermal properties of building materials based on its microstructure configuration that determines and associated heat transfer mechanisms. Finally, this would provide and insight into building envelope thermal performance based on its constituent material assemblage/configuration.

Nomenclature

λ	Thermal conductivity
λ_l	Lattice thermal conductivity
λ_e	Electronic thermal conductivity
L	Pore size
Gr	Grashof number
Pr	Prandtl number

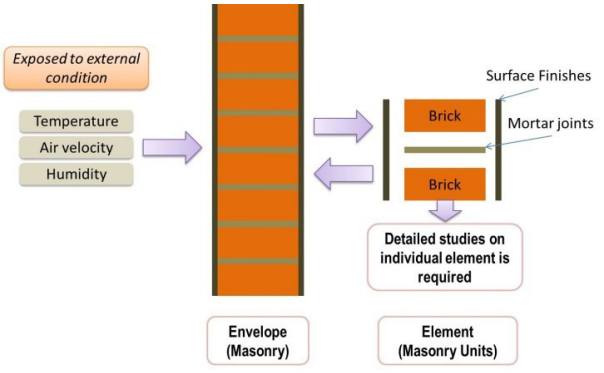

Fig. 1 The outline of building envelope thermal performance

2. Objective of the Study

The objectives of the study are as follows:

- Develop a rationale to understanding material microstructure: pore-particle geometry and constituent material/fluid properties
- Characterization of porous building materials based on its microstructure (pore and particle structure)
- Discern associated heat transfer mechanism based on material microstructure, specifically looking into role of pore parameters on building material thermal conductivity

Figure 2 illustrates the influence of materials microstructure on the thermal performance of building materials.

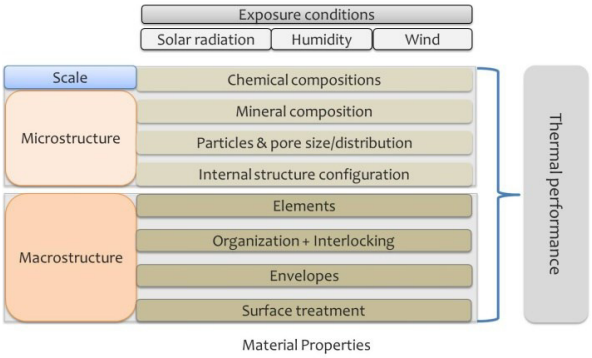

Fig. 2 Influence of material properties on building-envelope thermal performance

The current study attempts to establish a rational to characterize building-material thermal performance based on exposure conditions such as solar radiation, humidity and wind, and the scale of the material's inherent structures (microstructure and macrostructure). Material chemistry and mineral compositions, particle and pore size distribution and internal structure configuration at the microstructure level will influence the thermal performance under varying exposure conditions. Building elements, and its organization/configuration, different building envelopes, layers and its surface treatments are at macrostructure level which affects the thermal performance under different exposure conditions (see Fig. 2).

3. Building Materials

Most of the materials found are porous in nature, and it's nearly impossible to prepare a truly non-porous solid material [2]. Building materials are self-possessed network of pores and particles, generally in a consistent structure. It constitutes of solid matrix (as particle structure) and free space or voids (as pore structure). Understanding this complex network of constituent material and pores structure is important to their thermal performance behaviour. Materials porosity plays a major role in the heat transfer [3]. It is necessary to understand completely, the micro structure and its effect on heat transfer mechanism. Firstly, a comprehensive study of the materials microstructure such as pore structure, particle structures and associated parameters are required to visualize the material structure. Following which consequent heat transfer mechanism through the microstructure is discerned to reveal the thermal performance of the material a whole.

3.1. Characterization of the porous building materials

Porous building materials consist of two phases, namely; the solid matrix and pore space. Bhattacharjee [4] developed a model through geometrical idealization to study the heat transfer through porous building materials. Fig. 3 shows the schematic representation of the porous material structure.

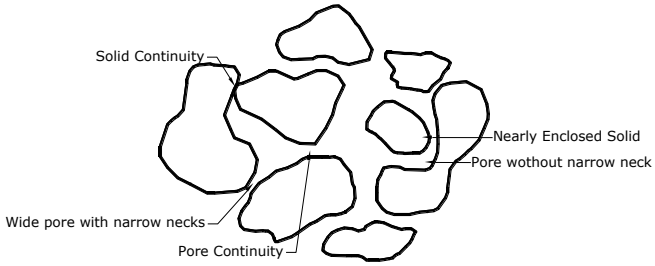

Fig. 3 Schematic representation of the porous material structure (Adapted from B. Bhattacharjee, 1989)

The IUPAC technical report [2] also describes the porous solids as illustrated in Fig. 4. The pores are classified into two categories according to their accessibility to an external fluid (moisture ingress). First category pores are completely isolated within the material described as closed pores; and second category pores constitute a continuous network with the external material surface and described as open pores. The scanning electron microscopy images show the internal porous structure of aerated aerocon block in Fig. 5, having the same pore structures as described in IUPAC technical report.

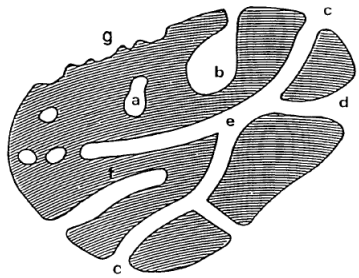

Fig. 4 Schematic cross-section of a porous solid (Source: Rouquerol et al. 1994)(a) closed pores, (b) ink bottled shaped, (c) open pore (or cylindrical), (d) funnel shaped, (e) through pores and (f) blind

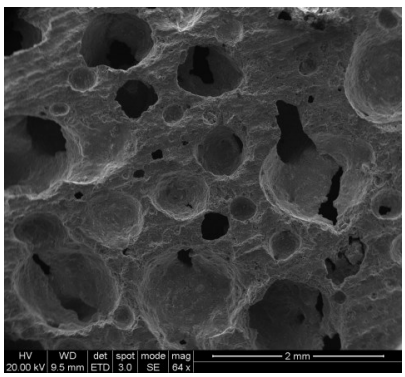

Fig.5 scanning electron microscopy image showing the internal porous structure of aerated aerocon block

4. Porosity: An Overview

Pore definition by WordWeb (wordweb.info) is "Any tiny hole admitting passage of a fluid (liquid or gas)". The spatial distribution of these pore form a network of pore structure.

Porosity is defined as the ratio of volume of the pores to the total or bulk volume of material. The porosity of building materials is generally composed of two fractions namely, Effective porosity (also called open porosity) and Ineffective porosity (also called closed porosity). The distance between two opposite walls of the pore is called Pore size or Pore width. The pore shape and pore connectivity is shown in Fig. 3; Materials with closed pores are useful in sonic and thermal insulation or lightweight structural applications [14]. Materials with open inter-connected pores are useful. Materials with the same total pore volume can exhibit entirely different characteristics, depending on whether the material contains a small number of large pores or a great number of small pores [6]. Pore size distribution in the material is one of the important fundamental information on the pore; it is the population of pores as a function of the pore width [15]. Pore size distribution of a material mainly depends on the internal structuring of the particles. Pore size and its distribution in a material depend on the particle size, shape number of particles in a unit.

The total pore volume, distribution of pores, their shape and inter-connections can affect the thermal conductivity of cement-based materials significantly. Thermal conductivity, as the main parameter describing heat transport, is often subject of measurements for various building materials. It plays a decisive role in the design of buildings keeping in view thermal resistance and fire protection [10]. To evaluate a building material's thermal conductivity (effective thermal conductivity), the corresponding thermal conductivities of the constituent layers needs to be known [11].In practice the thermal parameters of the porous composite material always represent the complex and mutual interaction of the solid and fluid phases in the heat transport process. Therefore it is difficult to produce the pure dense single solid phase component material for testing which would have the properties identical with the properties of the solid in a real porous composite [12].

4.1. Particle characterization

A Particle can be defined as a body having finite mass and internal structure with negligible dimensions. The spatial structuring of such particle finite mass to forms a definite material structure.

4.1.1. Classification of particle

Particle in solids can be classified based on size, shape, and mineralogical composition. Based on the literature, classification is available only for natural soil matrix based on its size from nano-size to macro-size. Table 1 summarizes the general particle size classification based on a review of literature. Particles can also classified based on shape to reveal the particle packing within a material, viz., well-rounded or spherical, rounded, sub-rounded, sub-angular, angular, flaky and elongated particles.

Table 1: General particle size classification

Particle size range (metric)							
< 1μm	1μm - 4μm	4μm – 75μm	75μm – 2mm	2mm – 4.75mm	4.75 – 64 mm	64 – 256 mm	256 mm <
Colloid	Clay	Silt	Fine sand	coarse sand	Gravel	Cobble	Boulder

4.1.2. Characterization of particle structure

Particle structure can be characterized based on destructive and non-destructive testing methods. In

destructive testing the test specimens are completely crushed for analysis.

4.1.2.1. Destructive testing

In this type of analysis, the most commonly adopted methods of analysis are sieve analysis, air elutriation analysis, electro resistance counting methods, sedimentation techniques, laser diffraction methods and acoustic spectroscopy or ultrasound attenuation spectroscopy.

4.1.2.2. Non-Destructive testing

These include optical counting methods (using electron microscope) and image analysis or photo analysis (using Scanning Electron Microscopy).

Characterization of particle structure can also be done based on the nature of formation

4.1.2.3. Compacted particles

When particles are naturally consolidated (without any application of external force, e.g. laterite) and artificially consolidated (with an application of external mechanical force, e.g., adobe, sun-dried bricks).

4.1.2.4. Cemented particles

When particles are bonded with externally binding agents to form a building block (e.g. Concrete blocks, soil-cement blocks)

4.2. Pore characterization

4.2.1. Classification of pore

Pores in solids can be classified based on size, shape, location, connectivity. Pore size is often the first or primarily classification used to characterize a pore [5]. Pores are classified based on their size extending from nano-pores to macro-pores. Table 2 summarizes pore-size classification based on a review of literature.

Table 2 Generalized pore size classification

Pore size							
Ultra micro-pores (0.3nm to 0.7nm)	**Super micro-pores (0.7nm to 2nm)**	**Meso pores (0.002µm to 0.05µm)**	**Macro pores (0.05µm to 0.5µm)**	**Small pores (0.5µm to 5µm)**	**Intermediate size pores (5µm to 100µm)**	**Large pores (0.1mm to 1mm)**	**Very large pores (>1mm)**
Micro-pore 0.3nm to 2nm							
Very small pores (0.3nm to 500nm)							

4.2.2. Characterization of pore structure

Pore structure is a very important micro-structural characteristic in a porous solid because it influences the physical and mechanical properties, and controls the durability of the material. The physical and mechanical behaviors of a porous material are strongly affected by the way in which the pores of various sizes are distributed within the solid [6, 2]. The pore structure is responsible for its physical properties such as permeability, electrical resistivity, convective dispersion, etc… [8]. Pore structure also affects thermal properties (such as thermal conductivity) of the materials. Porosity and pore sizes are equally important for other construction materials, namely mortar, brick, soil–cement, and concrete, etc. [7]. Bhattacharjee also report porosity and pore size distribution to play a major role in governing properties such strength, thermal conductivity and fluid permeability/hydraulic diffusivity [9].

Aligizaki [6] extensively worked on pore structure of cement-based materials, explains materials porosity influence on the properties of cement-based materials in various ways. Compressive strength and elasticity are primarily affected by the total volume of pores (total porosity); however, they can be influenced by the size and the spatial distribution of pores, maximum pore size, pore shape and connectivity. Permeability (Fluid permeability) and diffusivity (hydraulic diffusivity) are influenced by the total volume (total porosity), size shape (pore size distribution), and connectivity of the pores (pore connectivity). This has a critical bearing on moisture ingress in related mass transfer in the pores media. Shrinkage is largely a function of changes in surface energy at the pore walls and, therefore, depends upon the total surface area of the pore system.

Accurate characterization of the porous building materials is difficult due to the complex nature of pore and particle structuring. The complexity and variety of porous materials has led to the application of many experimental techniques for their pore characterization [2]. Rouquerol et al., further reveal that the selection of a method of characterization must start from the material and its intended use. The method chosen must concern with the phenomena involved in the application of the porous material. Thus suitable to select a method involving physical phenomena similar to the practical application so that the parameters studied are appropriate.

4.2.3. Pore structure characterization methods

Among the various techniques for the characterization of the pore structure, two broad methods include.

4.2.3.1. Direct Method

In this method, a direct investigation through microscope or physical image obtained from Scanning Electron Microscopy (SEM) methods can be used to determine the pore structure at surface and inside volume of materials, for better understanding the structuring of pores

4.2.3.2. Indirect Method:

An external stimulus is applied to the material and the material's response is measured using a suitable detector. The pore structure parameters are determined indirectly from properties such as adsorptive capacity, density, etc… [6]. The most commonly used indirect method for pore structure characterization are Mercury intrusion porosimetry (MIP), Gas adsorption, Nuclear magnetic resonance (NMR), etc…

4.2.4. Pore structure parameters

Characterization of a porous material provides information on the materials physical characteristics or parameters, such as total pore volume, surface area of pores, pore size distribution, pore shape, and pore connectivity. Aligizaki [6] describe the pore structure parameters for cement-based materials for general pores and air voids separately. General pores parameters include porosity, specific surface area, hydraulic radius, threshold diameter and pore distribution. Under air voids, the characterizations of pore structure of cement-based material are total air content, specific surface and spacing factor. The most important of these parameters are porosity and specific surface area of the pores. Jambor gives a brief explanation on the factors influencing development of the pore structure in cement composites in two stages. The first stage is determined by the composition of the mixture as well as by its mixing efficiency and compaction degree (preliminary pore structure). The second stage of the pore structure development is a consequence of the hydration, following the hardening of the cement composite [13], leaving being voids earlier occupied by water.

Materials composed of well graded particles of a wide range of sizes having a good representation of all sizes from nano to macro size particles, as shown in Fig. 6 (A), the pore size and its distribution will be uniform throughout the materials. If the materials composed of poorly graded particles, containing non-uniform size or single size of particles, as shown in Fig. 5 (B) and (C), the pore size and its distribution will also be non-uniform throughout the materials.

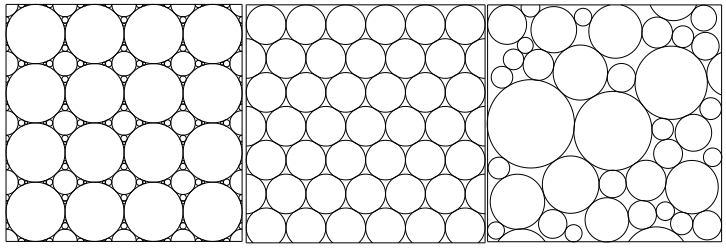

Fig. 6 (A) Well graded particles; (B) Single size or gap graded particles, and (C) Poorly graded particles

From mercury-porosimetry analysis parameters such as the pore-size distribution, the pore volume at different pressures, pore radii (such as average pore radius or median pore radius), the specific surface are, bulk density, apparent density and porosity can be calculate based on the pressure, volume of intruded mercury, sample mass and sample volume [16]. Fig. 7 shows the parameters that can be derived from pore-size distribution curves.

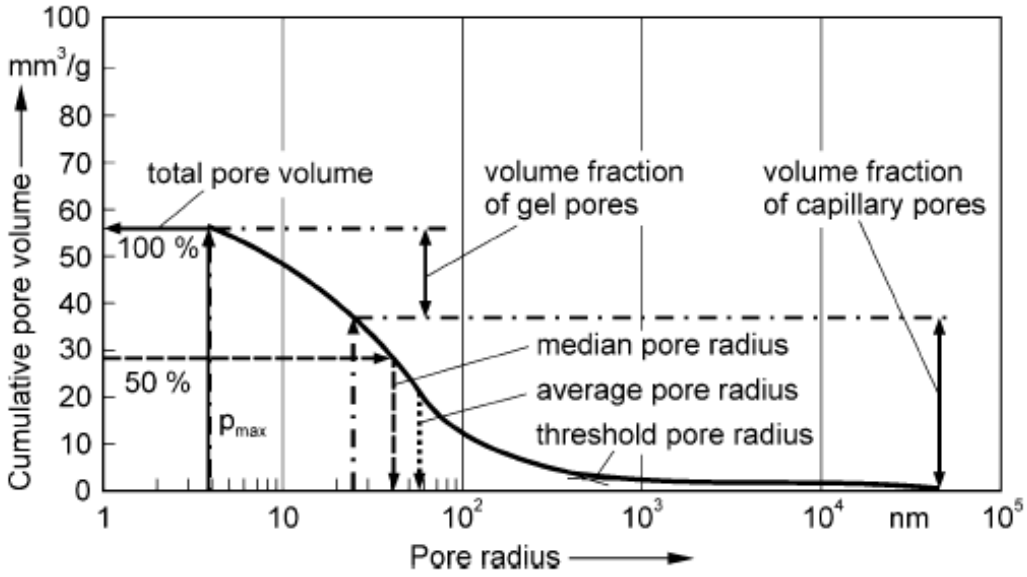

Fig. 7 Pore-Size Distribution curves to characterize building materials (Source: Rübner and Hoffmann)

Studies by Rübner and Hoffmann [16] provide a qualitative assessment of pore size distribution curves for few building materials such as hardened cement paste, ceramic tile and brick (see Fig. 8). Different class of materials reveals different intrusion/extrusion curves and resultant pore size distribution curves from a mercury-porosimetry analysis. The appearance of the pressure/volume curves and their hysteresis loops as well as the shape of the pore-size distribution curves provide an indication of the material's pore structure. This can be used to distinguish between different mineral content in building materials [16].

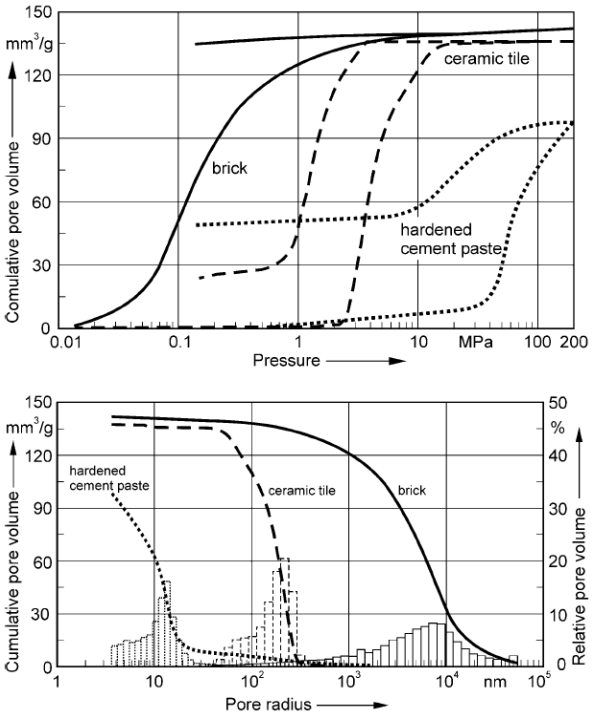

Fig. 8 Typical intrusion/extrusion curves of mercury-porosimetry analysis and corresponding pore-size distribution curves for different building materials (Source: Rübner and Hoffmann)

From the above studies, it can be clearly seen that different materials have different microstructure (from the pore size distribution studies).

5. **Heat Transfer mechanisms in Building Materials**

The heat transfer through the material is a combination of conductive, convective and radiative heat transfer components. A schematic representation of the heat transfer mechanism through the porous building-material microstructure is shown in Fig. 9. Conduction involves heat transfer through excitation of atoms, while convection involves heat transfer through molecule movement induced by differential temperature variation; radiative heat transfer involves heat-transfer through electromagnetic energy.

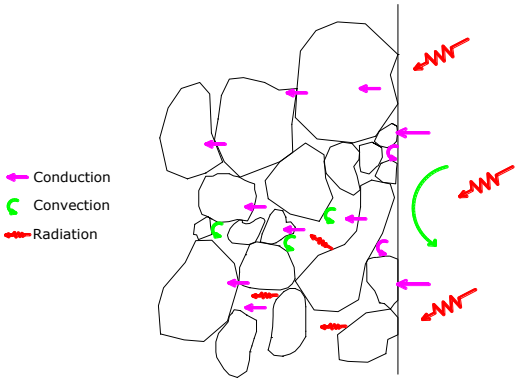

Fig. 9 heat transfer mechanisms through the porous building material

Understanding heat transfers through the building materials is a complex phenomenon due to the irregularity of the porous building-material microstructure. It is a challenge to quantify the modes of heat transfer through material solid matrix and voids [17]. In such materials, heat is propagated by thermal conduction through the solid phase, thermal conduction through the fluid phase, radiation between solid particles and convection in the fluid phase [18]. The heat transfer through different components is briefly explained below. These complex heat transfer processes involves many components such as [19, 20, 21, 22].

- Heat conduction in solid matrix/particles,
- Heat conduction through pore fluid (air or water),
- Heat conduction in micro-gaps that exist between particles,
- Particle contact heat conduction,
- Heat transfer through pore fluid,
- Radiation from solid surfaces of pores (particle to particle radiation in pores)

Conductivity is often sensitive to pores geometry. Parameters such as porosity, pores size and its distribution in the materials will affect the heat transfer through the porous building materials [23]. Considering the heat transfer in porous building material; the porosity, conductivity of the solid matrix (particle), and type of the fluid in the pores (water or air) are the main governing factors influencing the effective thermal conductivity.

Thermal conductivity is the property of a building material that plays a key role in all heat transfer calculations, and it governs the rate at which heat flows through the material. Effective thermal conductivity is a very important parameter in the thermal performance analysis of building envelopes [24].Hence, the measured (effective) thermal conductivity is the amount of heat flow under the unit temperature gradient for a unit area that encompasses some or the entire conductive, convective and radiative modes of heat transfer occurring within the material [7]. All these modes of heat transfer may be reduced to equivalent conduction by introducing equivalent thermal conductivity co-efficient applicable to the porous material [4]. Luikov reviewed a large number of published information on both experimental and theoretical thermal conductivity of capillary porous bodies, and explained the heat transfer characteristics by considered the coefficients of heat transfer to explain the equivalent coefficient of thermal conductivity of capillary-porous bodies [19, 20].

5.1. Heat conduction in solid matrix/particles

Heat conduction occurs through the solids matrix/particles in a material by electrons (particle collision) and photons conduction (lattice vibration). The thermal conductivity of material is a combined influence of these two mechanisms from Eq. (1).

$$\lambda = \lambda_l + \lambda_e \quad \textbf{(1)}$$

Where, λ_l and λ_e are the lattice and electronic thermal conductivities

In metals, heat conduction through electron collision is effective and dominant; in non-metal and insulators heat conduction through lattice vibration is effective, which do not have many free electrons.

5.2. Heat conduction through pore fluid (air or water)

This component of heat transfer mainly depends on the type of the fluid present in pores. Fluids may be air or water; thermal properties of fluids vary with respect to their chemical composition and state (phase). For example, water conducts heat nearly twenty five times more than air [25].

Loeb explains heat conduction through pore fluid, especially through gases, to be dependent on the mean free path (λl), which is a function of temperature and pressure. This is valid when pore dimensions are larger

than the mean free path. However, gas conductivity falls below the free gas value if pore structure is finer than mean free path, in which case there will be gas molecule–wall collisions (Knudsen conduction) [26]. Clyne, et al [27] schematically illustrate this heat transfer mechanisms in porous materials in Fig. 10. From kinetic theory, the mean free path is the average distance covered by a moving particle between collisions with other moving particles. Jennings explain that the mean free path in air varies also with relative humidity (moisture content in air), along with temperature and pressure [28].

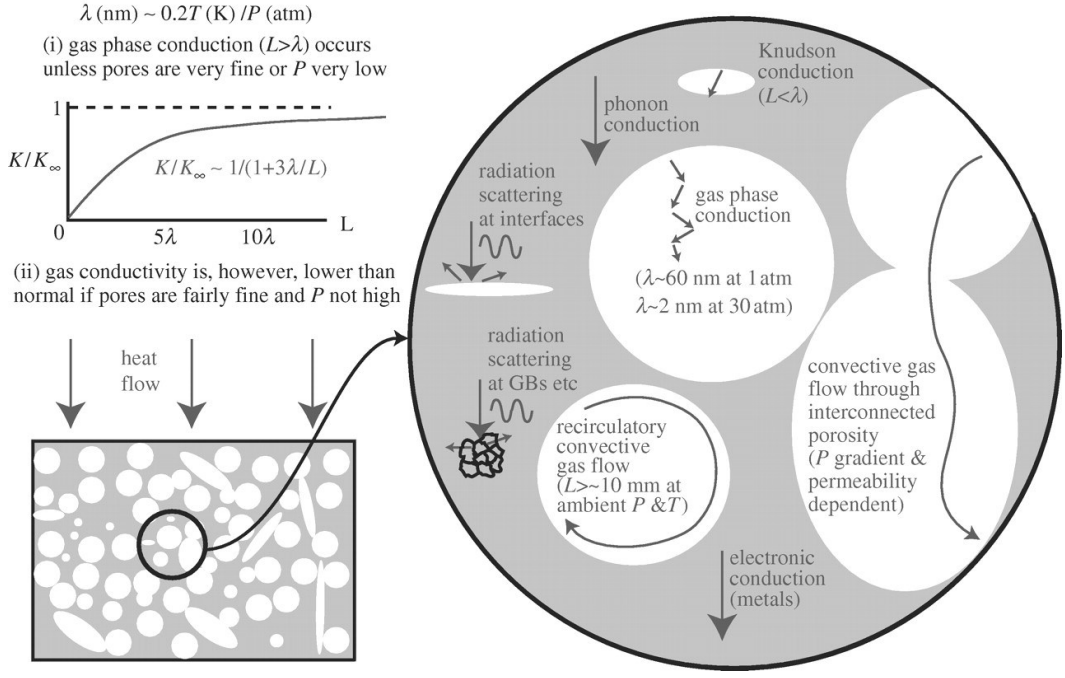

Fig. 10 Mechanisms of heat transfer in porous materials (Source: Clyne, et al. 2006).

5.3. Particle contact heat conduction

Luikov explain the importance of the particle-contact heat conduction. This phenomenon can be neglected at normal temperatures and pressures, but might be very substantial at low pressures and moderate temperatures [19]. Yun and Santamarina investigated the effects of thermal conductivity on contact quality and number of contacts per particle (determined by packing density, particle shape and particle size distribution) [29]. Fig. 11 illustrates the particle-contact and other heat transfer paths in a material.

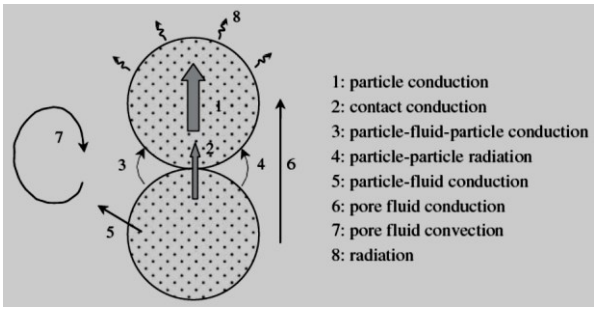

Fig. 11 Summary of heat transfer paths in materials (Source: Yun and Santamarina 2008).

5.4. Heat transfer through pore fluid,

The heat transfer through pore fluid mainly depends on the type or nature of the fluid present in pores, and primarily occurs through convection. Fluids may be air or water. Heat exchange or transfer from the particle to fluid in pore is eventually by convection.

5.5. Radiation from solid surfaces of pores (particle to particle radiation in pores)

The radiative component is more significant at very low densities at a high temperature wherein effective coefficient of heat conductivity of porous building materials will be high [30]. At very high temperatures the pores themselves offer little resistance leading the porous body to conduct as though the pores were solid. With increasing temperature the apparent thermal conductivity of loose and porous insulating materials becomes greater, because the conductivities of the solid substance and of the gas in the pores, and the inner radiation increase [25]. The scale of the pore structure (and the grain size) can also affect radiative heat transfer, since radiation is effectively scattered by interfaces (grain boundaries). A fine-scale structure results in increased scattering and reduced transmission. However, an increase in the scale increases the possibility of convection within or between pores [31, 32, and 33]. Luikov studied the effect of the radiative heat transfer in porous materials for different pore sizes at different temperatures, and concluded that radiative heat transfer can be neglected for a pore diameter smaller than 5mm. Luikov also showed that with (Gr.Pr) < 1000 convective heat transfer in closed pores can be neglected and that the heat transfer through the fluid layer in the gap occurs by conduction [19]. Clyne et al showed the effect of the temperature and pressure on the Grashof number. Convection is significant if the Grashof number exceeds 1000. Fig. 12 illustrates this to be valid when the pore size is large (L > ~10 mm). The study concludes that closed-cell convection can be neglected for most porous materials, under commonly encountered conditions. In open-cell materials, on the other hand, convective heat transfer may be highly significant, depending on the connectivity and scale of the pores.

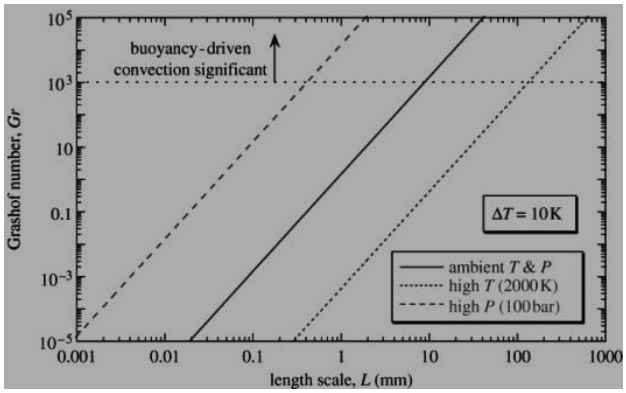

Fig. 12 Dependence of Grashof number on length scale (pore size), for different pressures and temperatures (Source: Clyne, et al. 2006)

6. **Effects of pore parameters on thermal conductivity of materials**

Sugawara and Yoshizawa [23] experimentally investigated the thermal conductivity of porous materials and the effects of porosity and temperature on thermal conductivity. The porous materials reveal different characteristics; depend on the total pore volume and presence of a small numbers of large pores or a large number of small pores. If the thermal conductivity of the solid matrix is were to be larger than that of the fluid (air or water) in the pores, the thermal conductivity decreases with increase in porosity. Similarly, if the thermal conductivity of the solid matrix were to be smaller than that of the fluid (air or water) in the pores, the thermal conductivity increases with increase in porosity [23]. Iwan Sumirat et al. [34] presented an

expression for the dependence of porosity on thermal conductivity. The expression reveals that the thermal conductivity of nano-porous materials depends on the pore size. If the average pore size is close to the photon mean free path at zero-porosity, the phonon-pore scattering significantly reduces the thermal conductivity.

The pore parameter entirely depends on the particle packing. In building materials this pore parameter depends on the density of the materials. Rübner and Hoffmann [16] studied the variation of total pore volume (is a one of the pore parameter) under different bulk density of same standard brick materials. They found that denser the materials lesser would be the total pore volume, thereby resulting in the conductive heat transfer to be more dominant in comparison with other modes of heat transfer [16]. Fig. 13 shows the variation of total pore volume under different bulk density of same standard brick materials.

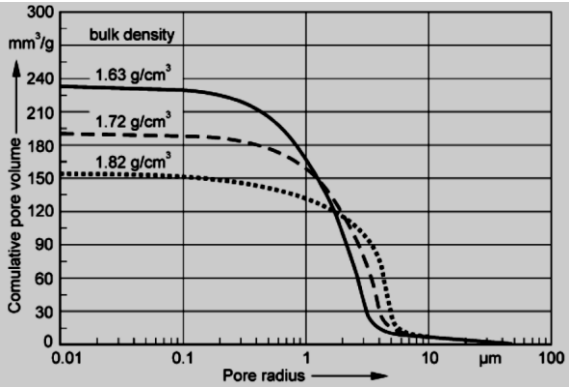

Fig. 13 Variations in bulk density and in pore-size distribution of standard (Source: Rübner and Hoffmann)

Thus, materials with the same total pore volume can exhibit entirely different characteristics, depending on whether the material contains a small number of large pores or a great number of small pores.

7. Building Envelope

A building envelope essentially comprises an assembly of various building materials. Its thermal performance is thus dependent on its constituent building-material configuration/s. Given the fact that the thermal performances of individual materials are governed by their microstructure, it is easy to appreciate the role of microstructure on the building-envelope performance. As discussed in the earlier sections, heat transfer through porous material mainly depends on the material forming constituents (type of particle, shape, size and particle structuring) and their microstructure (pore structure). Further, it is also evident that it is challenging to control/regulate the material at its microstructure level.

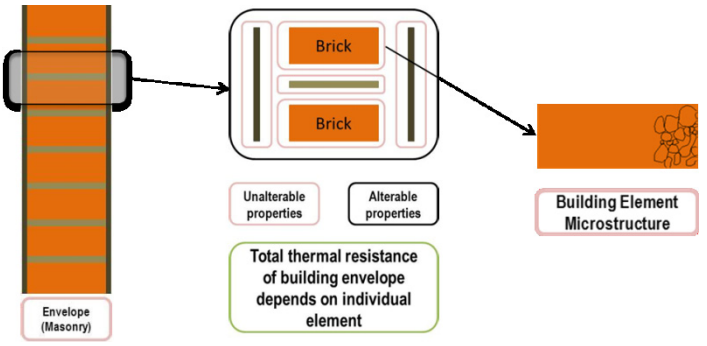

Fig. 14 shows the building envelope and material structuring (macro and micro structure)

In building envelope, individual material constituents and their associated properties are unalterable. Structuring/changing of material structure at the micro level is difficult. Internal structuring of the material plays a major role in regulating the heat transfer through it. The arrangement of different materials to form a building envelope can be designed to obtain required thermal performance of envelope. The envelope constituents (individual material) and its materials configurations can be altered or rearrange.

The thermal performance of building envelope can be easily modified by altering its materials configuration. Fig. 14 illustrates the building envelope in terms of its material structure, and the alterable and unalterable properties of building envelope. Building-material configuration/s to form building envelope can be altered by appropriately arranging the materials to obtain required performance. Building materials properties that are easily alterable (packing density, composition and mix-proportions) are distinct from those that are unalterable (micro-pore size and geometry, inherent mineral property).

8. Conclusions

A building envelope is made-up of several individual elements such as brick, mortar, surface finishes, external coatings, etc. It regulates the indoor thermal environment in response to the external environment. However, the ability of a building envelope to regulate indoor thermal comfort is determined by its constituent material configuration, which in turn is determined by the constituent material's individual microstructure. The current paper attempts to provide an appreciation of building-material thermal performance based on its microstructure. Thus, the constituent pores and particles of constituent building materials are important parameters influencing how a building envelope regulates indoor thermal comfort.

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